NAVSEA
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Lithium Ion Testing at NSWC Crane in Support of NASA Goddard Space Flight Center

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CRANE DIVIDSON, NAVAL SURFACE WAREFARE CENTER
Crane Indiana

NASA AEROSPACE BATTERY WORKSHOP – Nov 16-18, 2010
Huntsville, Al

INTRODUCTION

- QUALLION 15 Ahr Lithium-Ion Cells
  - LEO Life Cycle Test
- LITHION 50 Ahr Lithium-Ion Cells
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- ABSL 5 Ahr Lithium-Ion Battery
  - LRO-LLO Life Cycle Test
  - SDO-GEO Life Cycle Test
- A123 40 Ahr Lithium-Ion Battery
  - GPM Life Cycle Test
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QUALLION 15 Ahr Lithium-Ion Cells
LEO Life Cycle Test

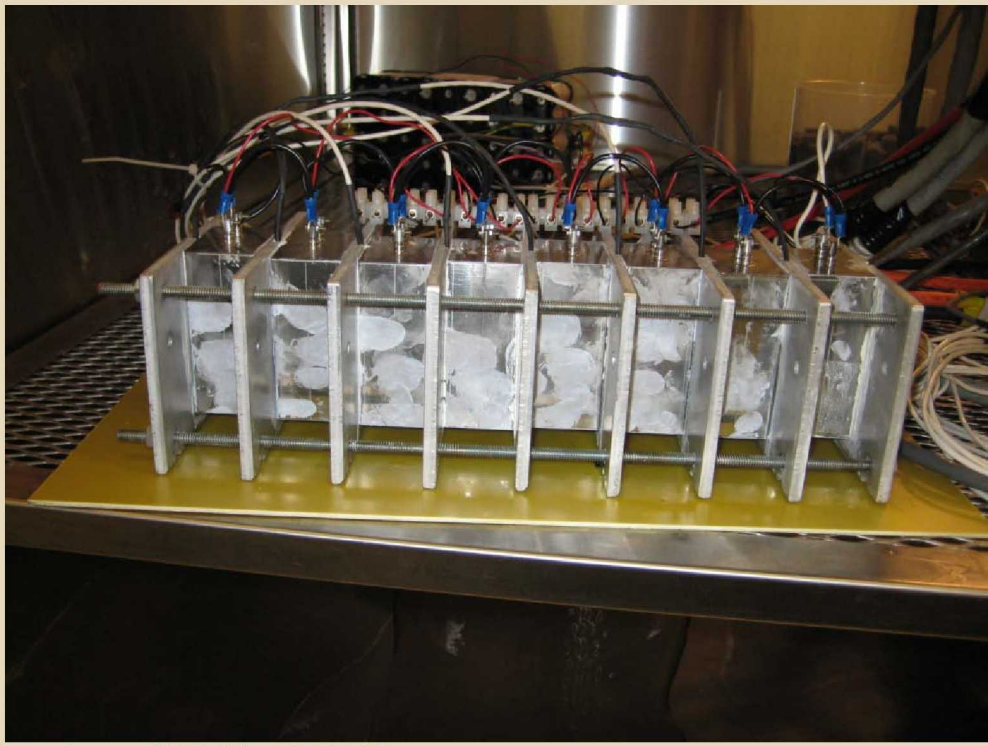
QUALLION 15 Ah (G001QL) TEST PARAMETERS

Test Pack: Eight 15 Ah $LiNiO_2$ cells in series

Manufacturer: QUALLION

Initial Evaluation:

Actual Capacity at 20°C = 14 Ahr,
0°C = 12 Ahr,
40°C = 15.6 Ahr



Initial Parameters:

Test Temperature 20°C
Pre-Life Cycle Charge:
C/10 charge to 32.8V,
taper to C/100

LEO Life Cycle: 6A discharge for 48 minutes (32% DOD)
7A charge to 31.6V, taper for 65 minute charge time
80% DOD Deep Discharge
Every 30 days: 7A charge to 32.8V, taper for 65 minute charge time
6A discharge for 120 minutes (80% DOD)
Return to LEO Life Cycle profile

QUALLION 15 Ah (G001QL) TEST HISTORY

9 December 2004 – Began Initial Evaluation test

22 February 2005 – Began life cycling
6A discharge for 48 minutes (32% DOD)
7A charge to 31.6v, Taper for remainder of 65 minutes

9 May 2005 – Changed discharge rate for Deep Discharge to 4.5A for 160 minutes

8 June 2005 – Changed Life Cycling charge rate to 6A (Cycle 1217)

6 May 2008 – LEO Life Cycle profile changed to (Cycle 13,453):
9.6A discharge for 30 minutes (32% DOD)
6.5A charge to 31.6v, Taper for remainder of 60 minutes

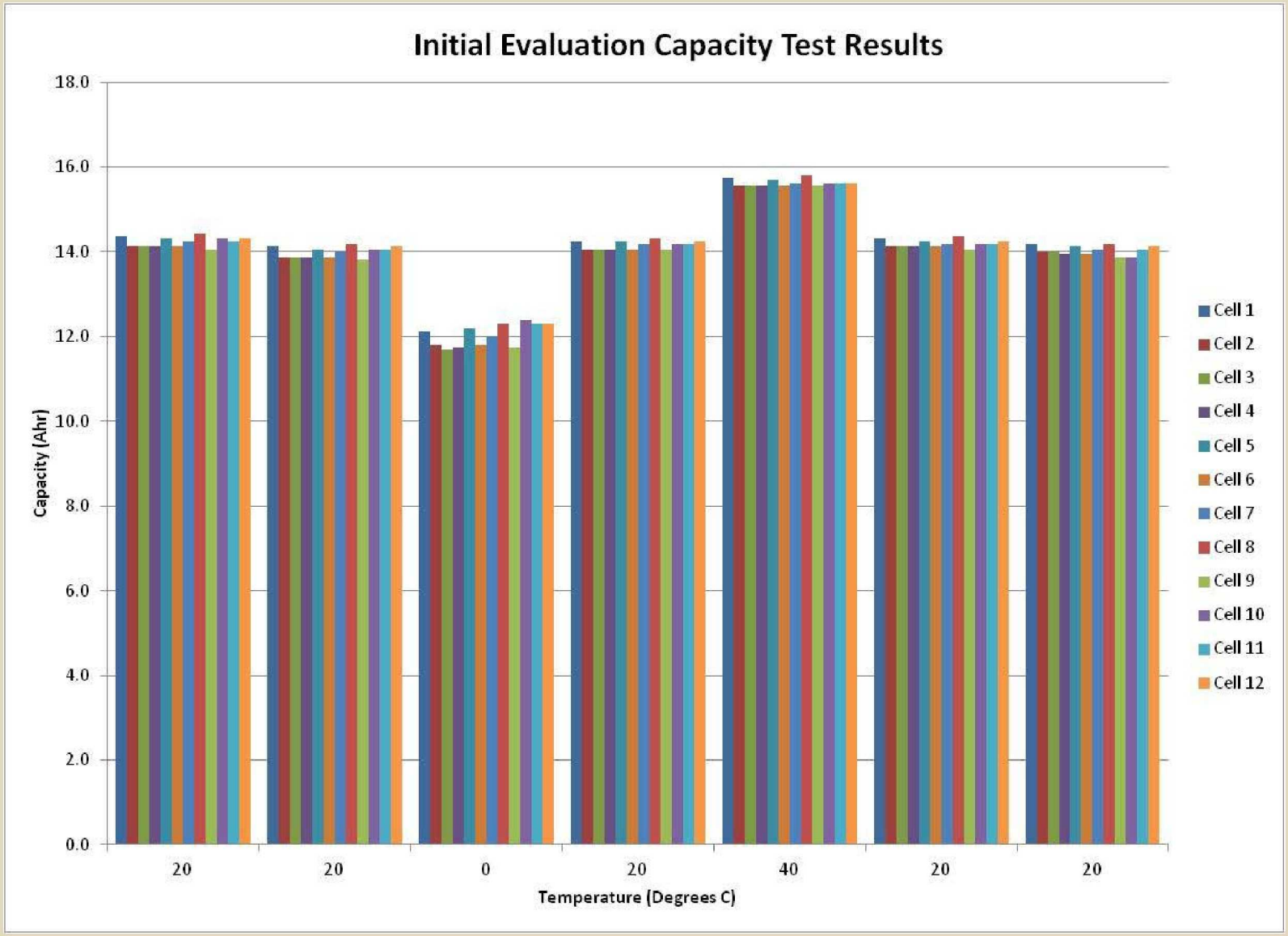
20 May 2008 – LEO Life Cycle profile changed to (Cycle 13,677):
12.0A discharge for 30 minutes (40% DOD)
8.1A charge to 31.6v, Taper for remainder of 60 minutes
80% DOD Deep Discharge Cycle Eliminated

8 September 2008 – Cycle 15,426. Test Pack was moved from its location in Building 3235 to a new test system in building 3287 due to renovation of the building 3235 area.

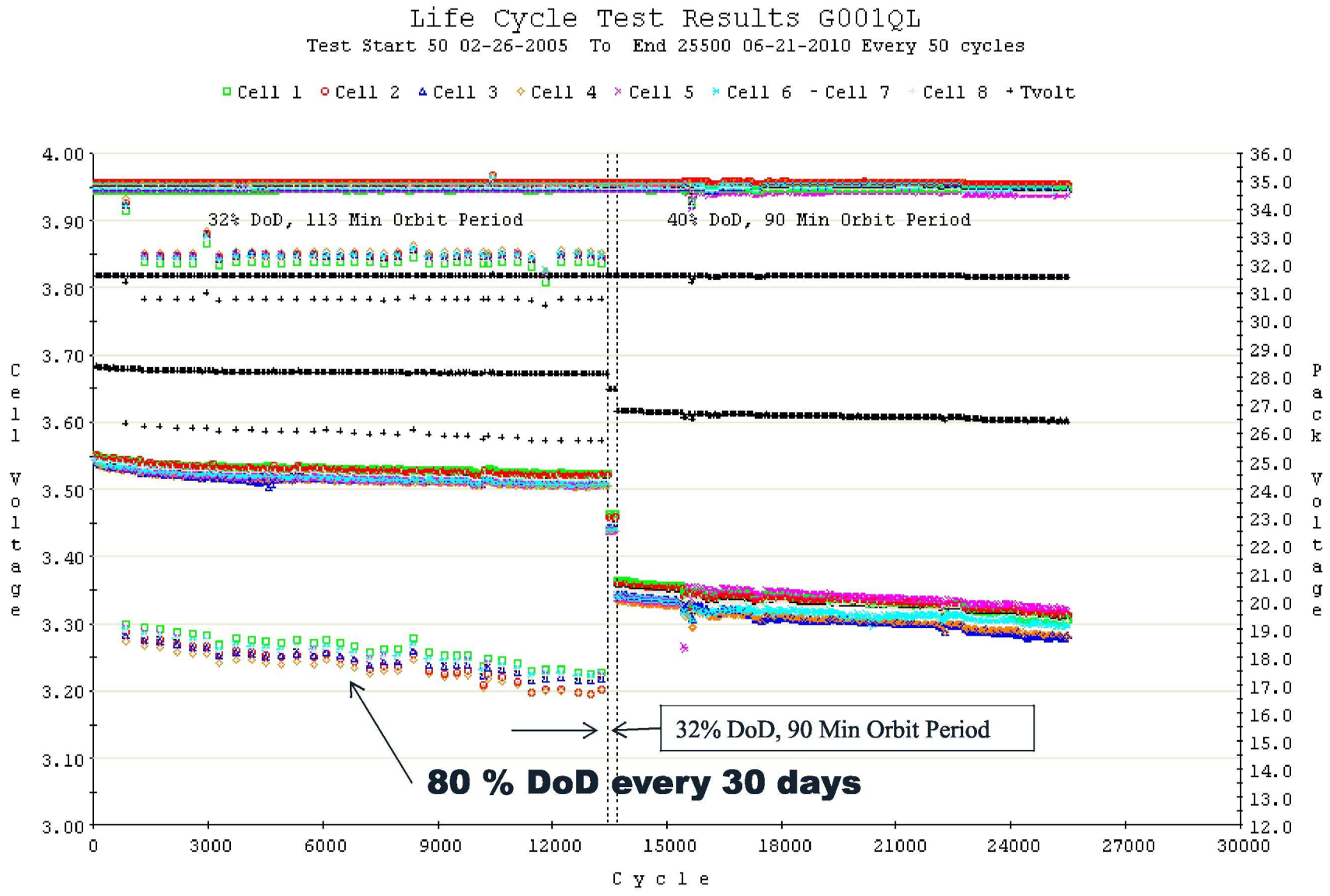
23 June 2010 – End LEO Life Test – 25,533 cycles 5 years, 4 months
Performed Post Cycle Test

30 August 2010 – Report GDD GXS 10-093

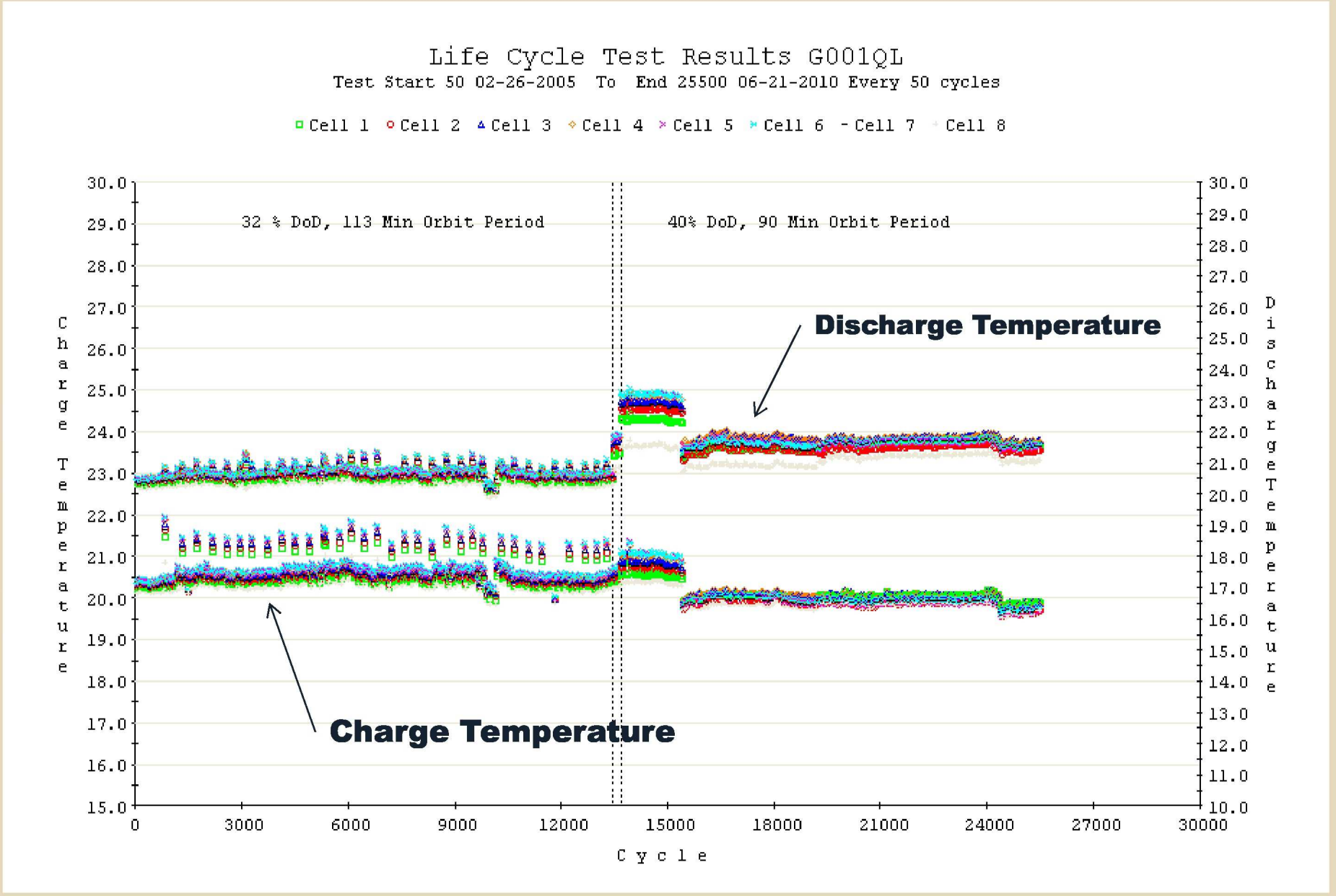
QUALLION 15 Ah (G001QL) Initial Evaluation Results



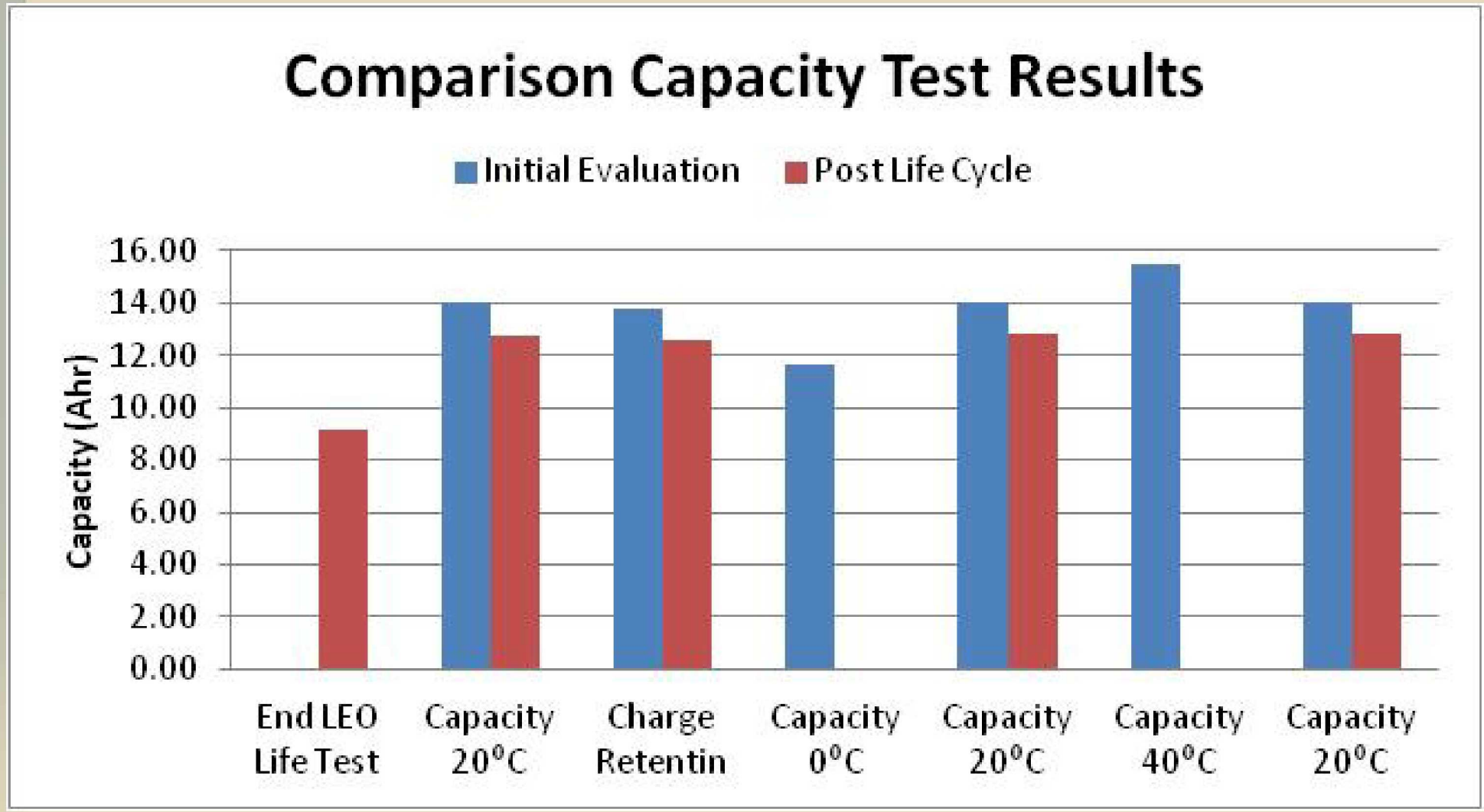
QUALLION 15 Ah (G001QL) Life Cycle Test Results



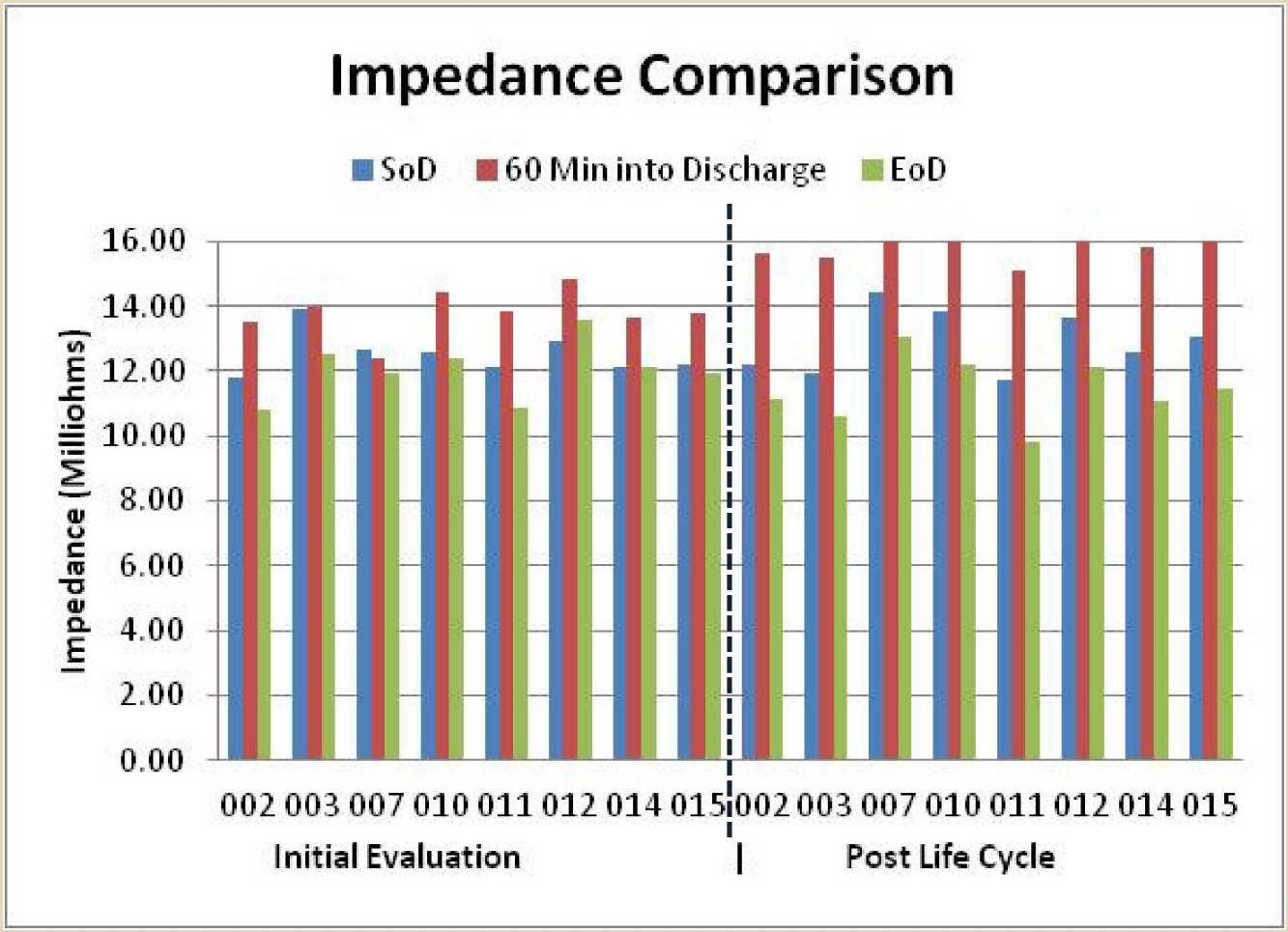
QUALLION 15 Ah (G001QL) Life Cycle Test Results



QUALLION 15 Ah (G001QL)
Post Life Cycle Test Results



QUALLION 15 Ah (G001QL) Post Life Cycle Test Results



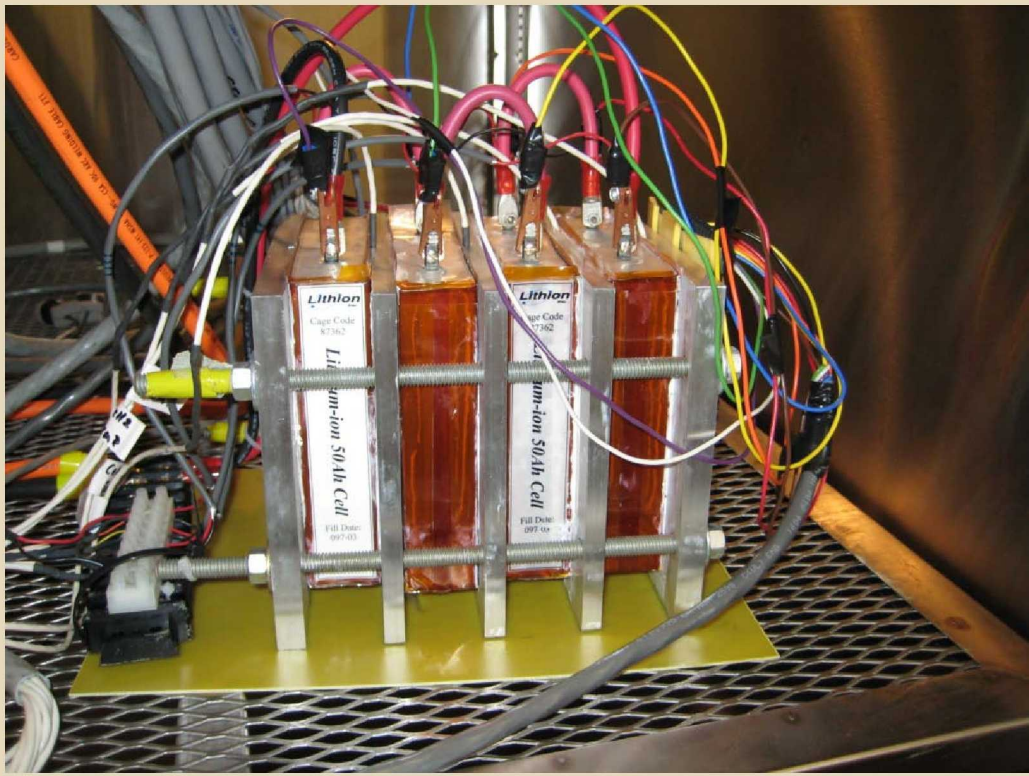
LITHION 50 AHR LITHIUM-ION CELLS LEO LIFE CYCLE TEST

LITHION 50 Ahr Lithium-Ion Cells Test Parameters

Test Pack: Four 50 Ah $LiNiO_2$ cells in series
Manufacturer: YARDNEY TECHNICAL PRODUCTS INC.

Initial Evaluation:

Actual Capacity at 20°C = 57.7 Ahr,
0°C = 56.6 Ahr,
40°C = 61.0 Ahr



Initial Parameters:

Test Temperature 20°C
Pre-Life Cycle Charge:
C/10 charge to 16.4V,
then taper to C/100

Every 6 months:
22A Charge to 16.4V,
taper for 65 minute charge time
15A Discharge for 160 minutes (80% DOD)
Return to LEO Life Cycle profile

LEO Life Cycle: 25A discharge for 48 minutes (40% DOD)
22A charge to 15.8V, taper for 65 minute charge time

LITHION 50 Ahr Lithium-Ion Cells Test History

24 March 2005 – Began Initial Evaluation

28 April 2005 – Began life cycling – The cells began diverging.

6 February 2007 – Cycle 7654. To decrease cell divergence, increased EOCV from 15.8V to 16.4V and EUVL from 4.2V to 4.3. Was not successful.

23 March 2007 – Cycle 8204. Attached Crane Developed Resistor Cell Balance Unit. The EOCV was lowered back to 15.8V and EUVL to 4.2

30 March 2007 – Cycle 8290. Removed Crane Developed Resistor Cell Balance Unit.

17 April 2008 – Cycle 12,520. Crane Developed Resistor Cell Balance Unit attached again because of increasing cell divergence. To be removed in 6 months.

4 September 2008 – Cycle 14,274. Test Pack was moved from its location in Building 3235 to a new test system in building 3287 due to renovation of the building 3235 area.

20 October 2008 – Cycle 14,845. Crane Developed Resistor Cell Balance Unit removed.

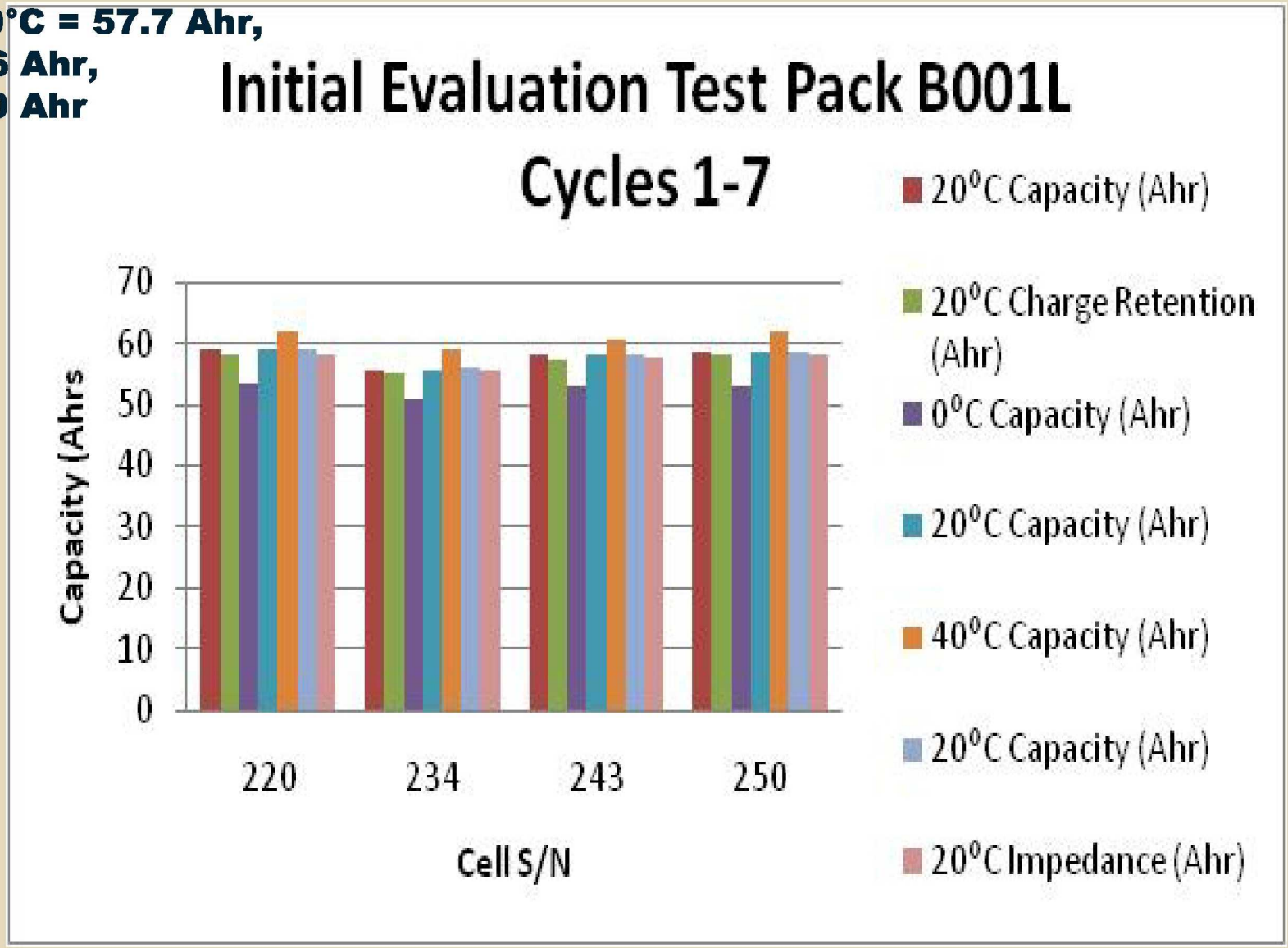
3 March 2009 – Cycle 16,493. Crane Developed Resistor Cell Balance Unit reinstalled on pack. Resistance Balance Circuit remained on for remainder of test,

23 June 2010 – Discontinued. Competed 22,461 cycles 5 years Performed Post Cycle test.

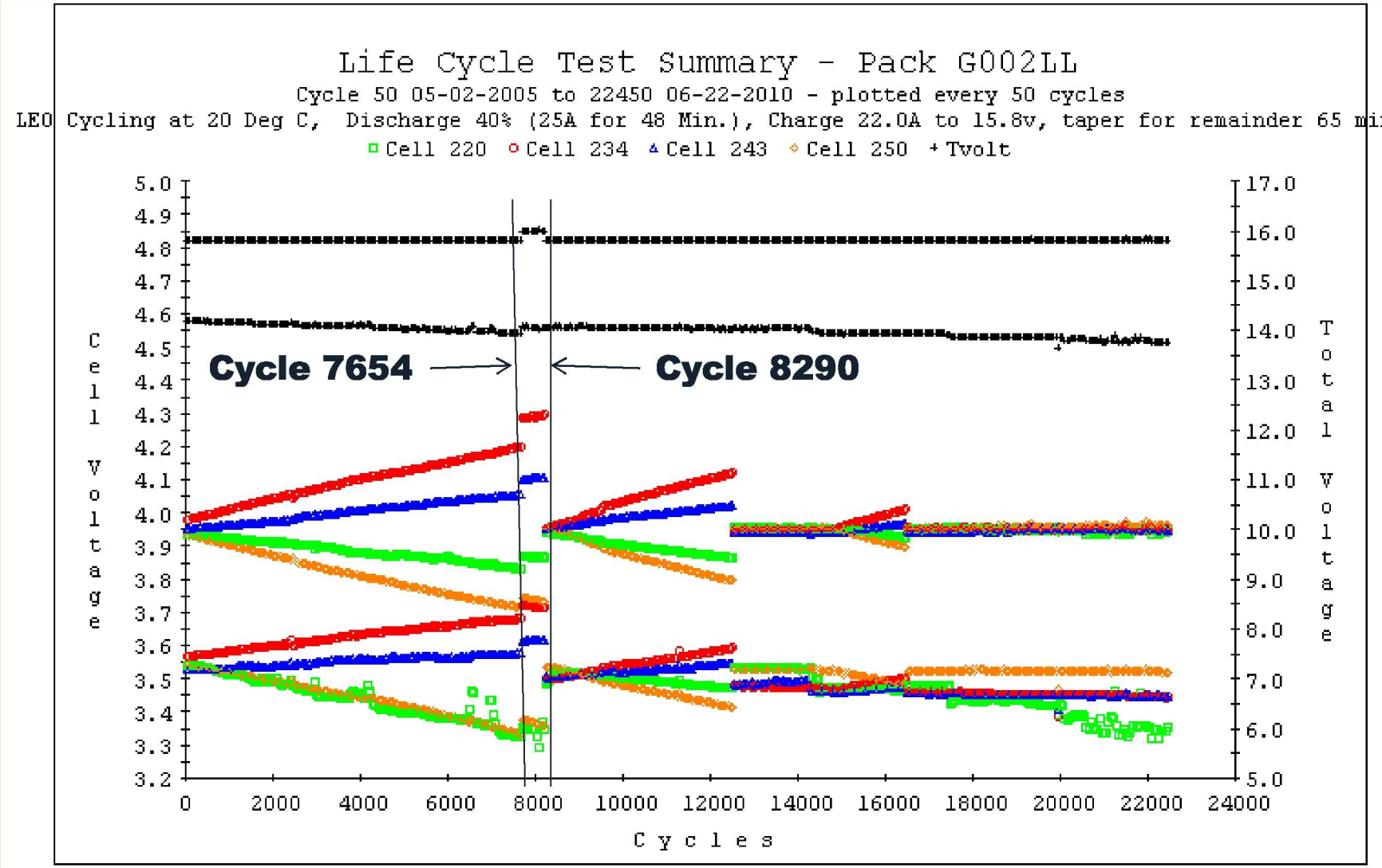
24 September 2010 – Report GDD GXS 10-107

LITHION 50 Ahr Lithium-Ion Cells Initial Evaluation Summary

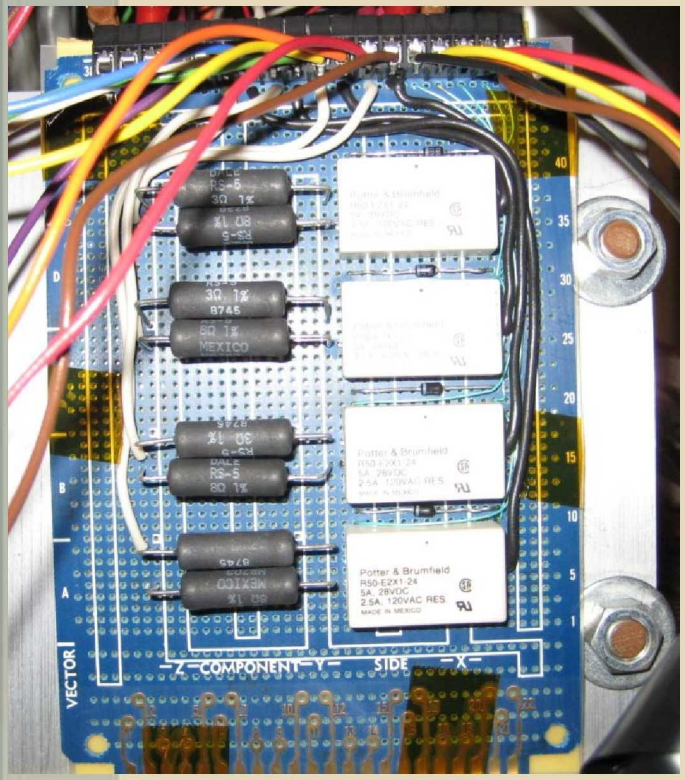
Capacity at 20°C = 57.7 Ahr,
0°C = 56.6 Ahr,
40°C = 61.0 Ahr



LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary

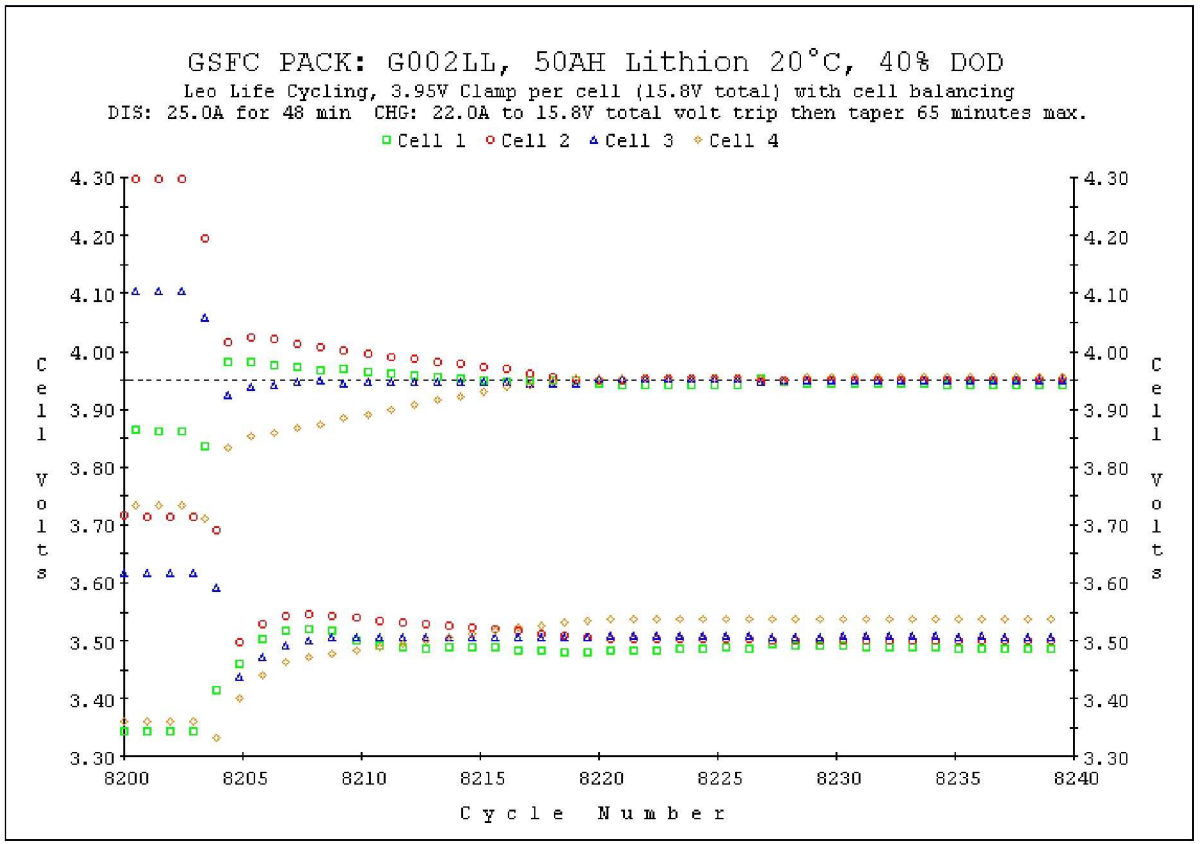


LITHION 50 Ahr Lithium-Ion Cells LEO Life Cycle Test

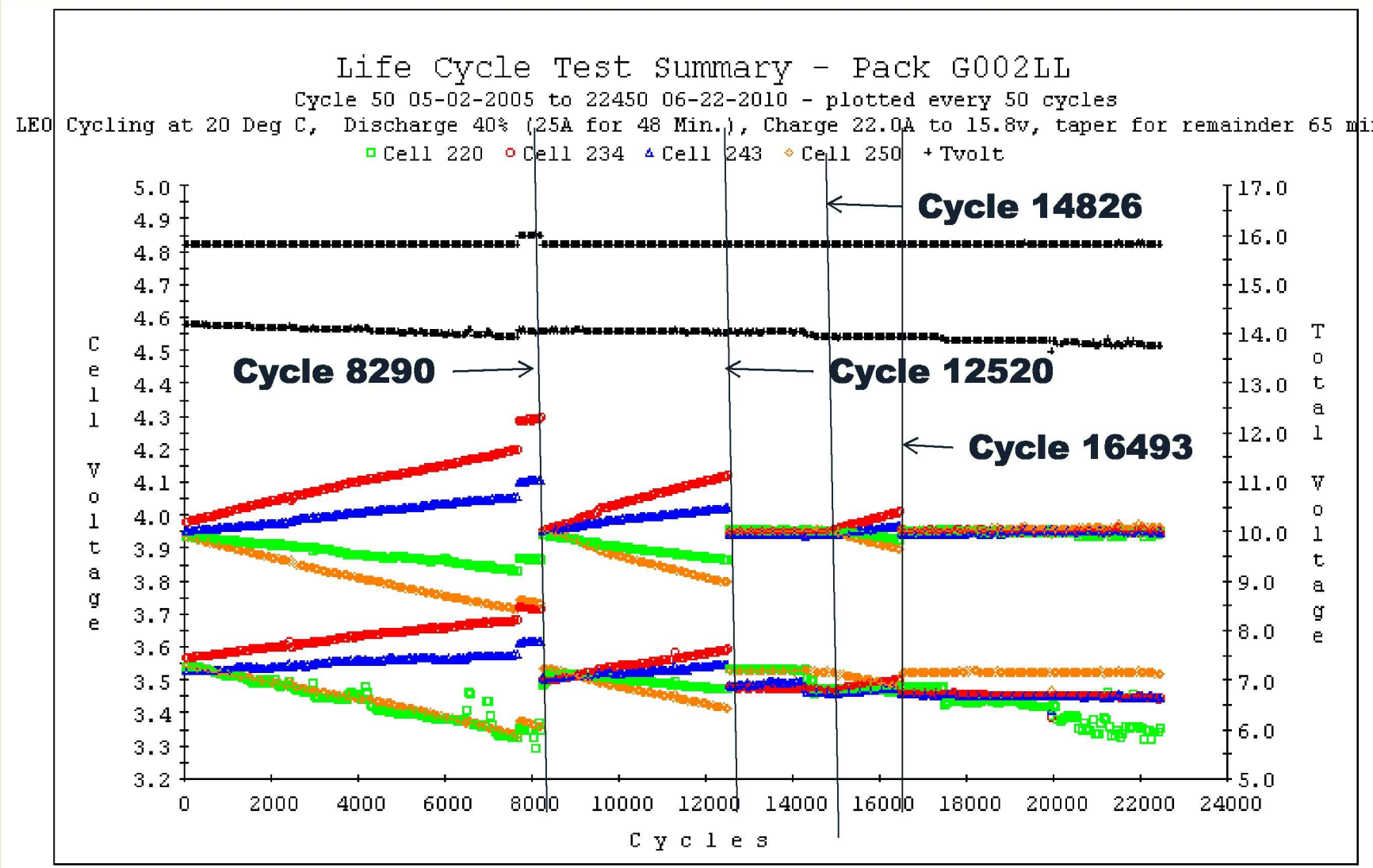


Cycle 8203	End of Discharge Voltage	End of Charge Voltage
Cell #1	3.34283	3.83635
Cell #2	3.71513	4.19647
Cell #3	3.61626	4.05788
Cell #4	3.36023	3.71006
Voltage Spread	**0.37230**	**0.48641**

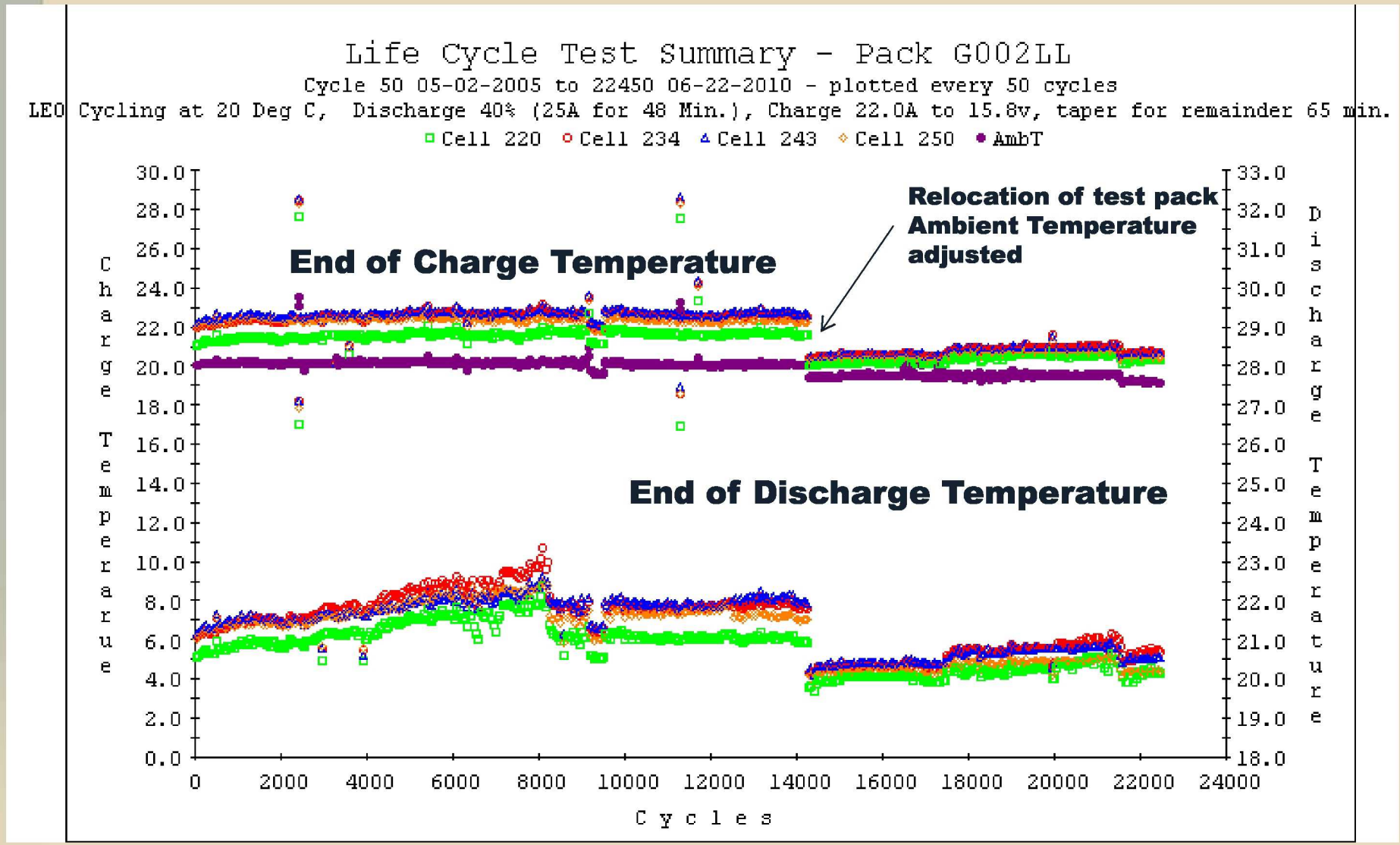
Cycle 8240	End of Discharge Voltage	End of Charge Voltage
Cell #1	3.48702	3.94228
Cell #2	3.49946	3.95175
Cell #3	3.50563	3.95135
Cell #4	3.53681	3.95472
Voltage Spread	**0.04979**	**0.01244**



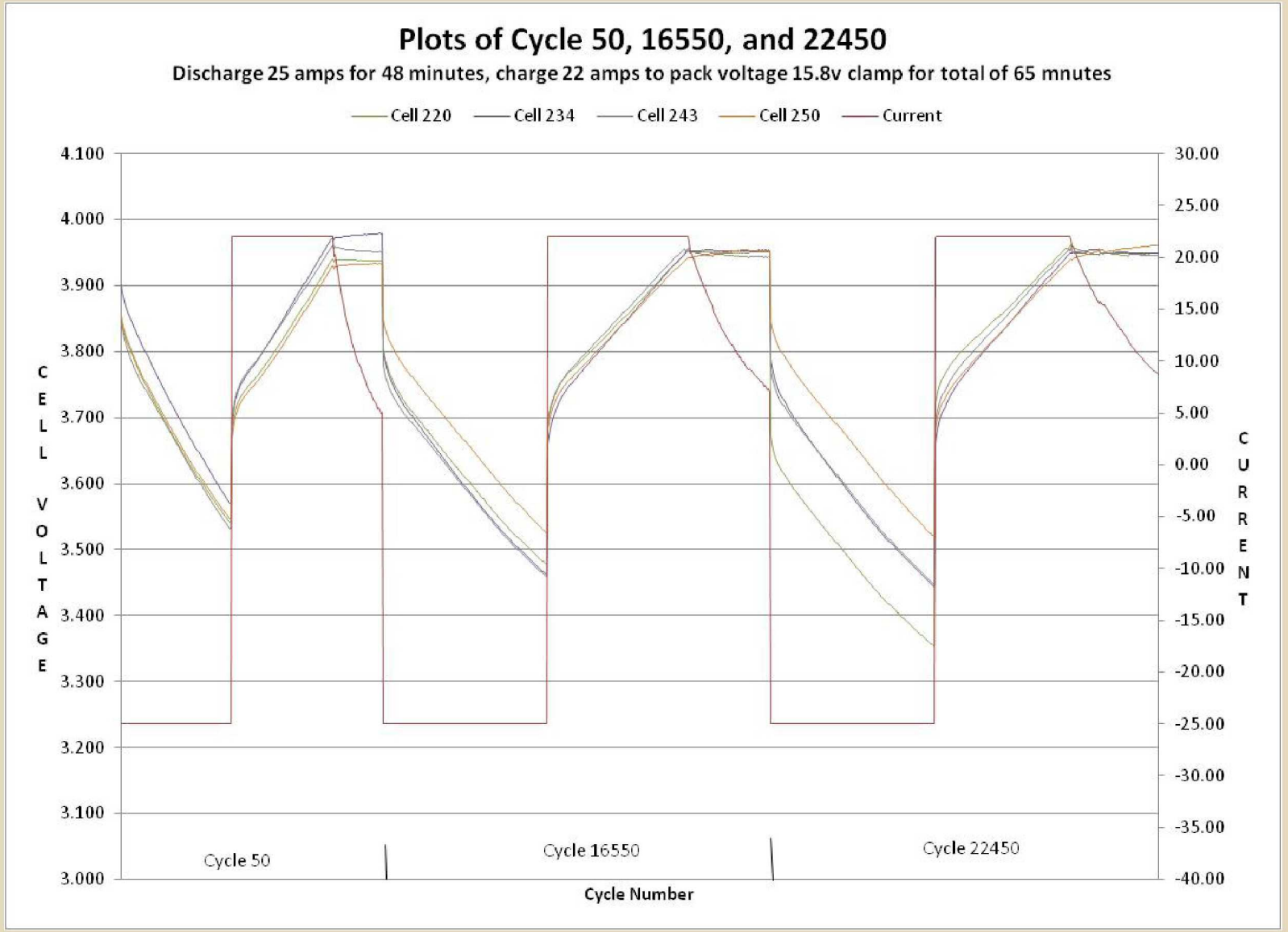
LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary



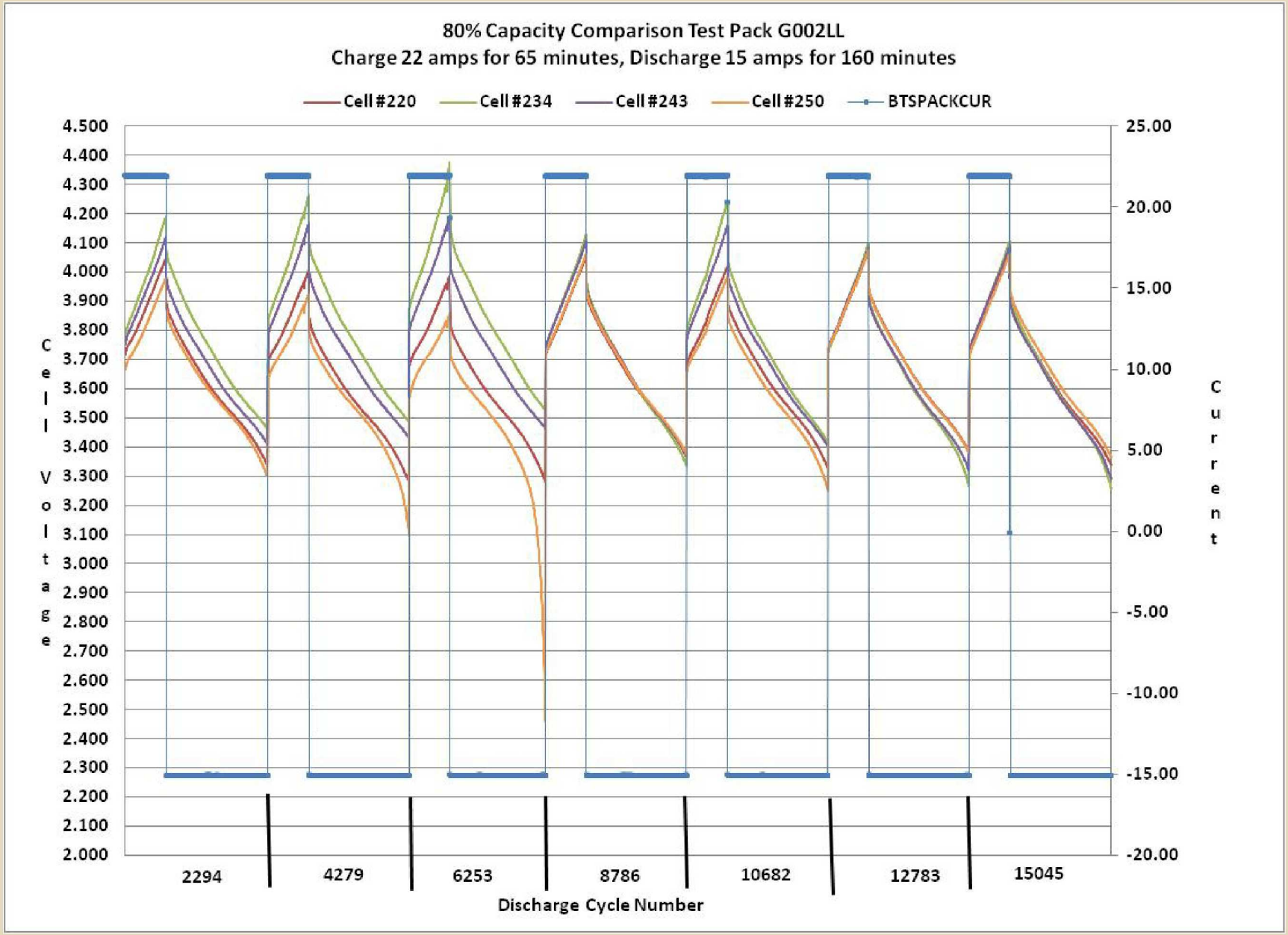
LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary



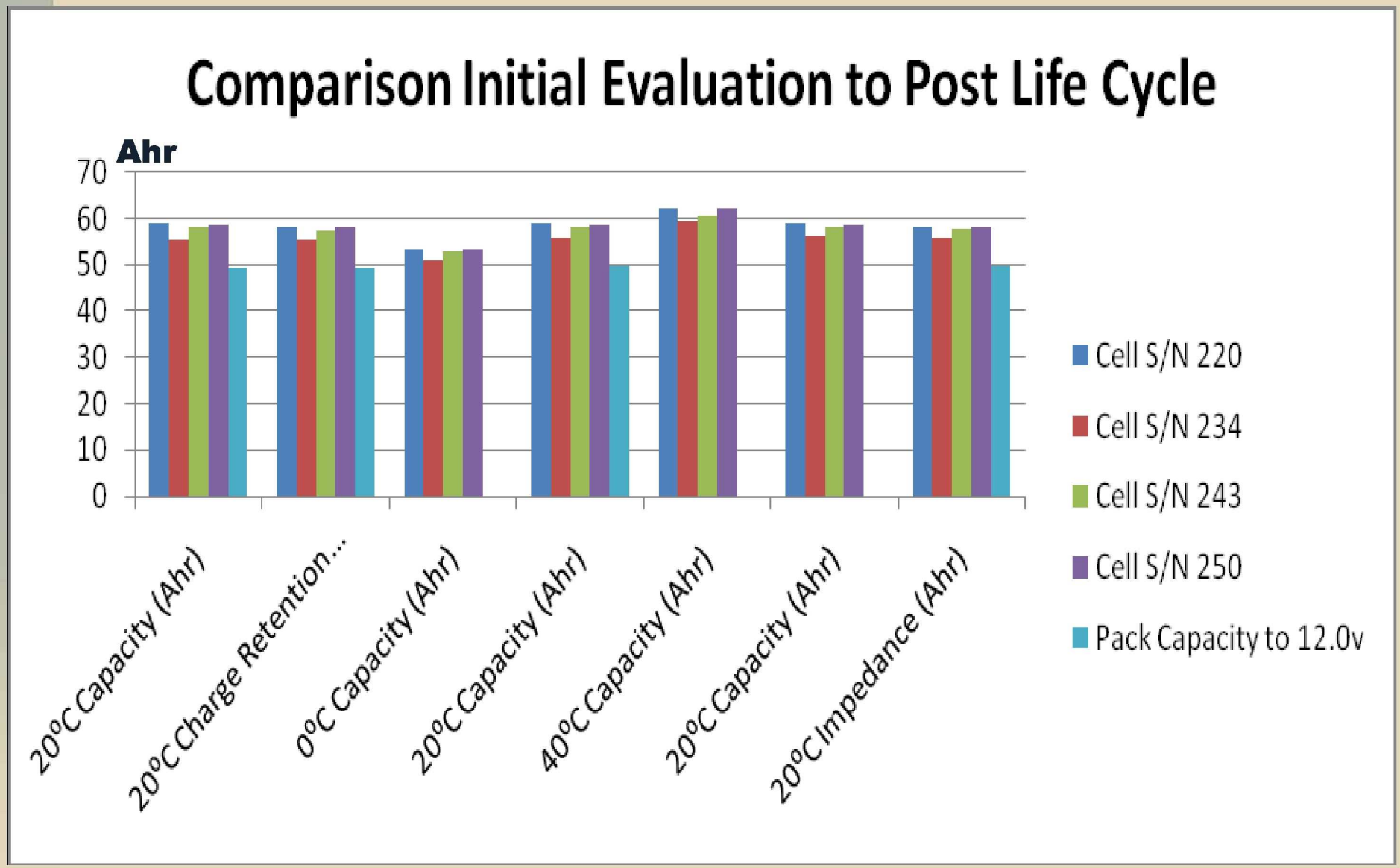
LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary



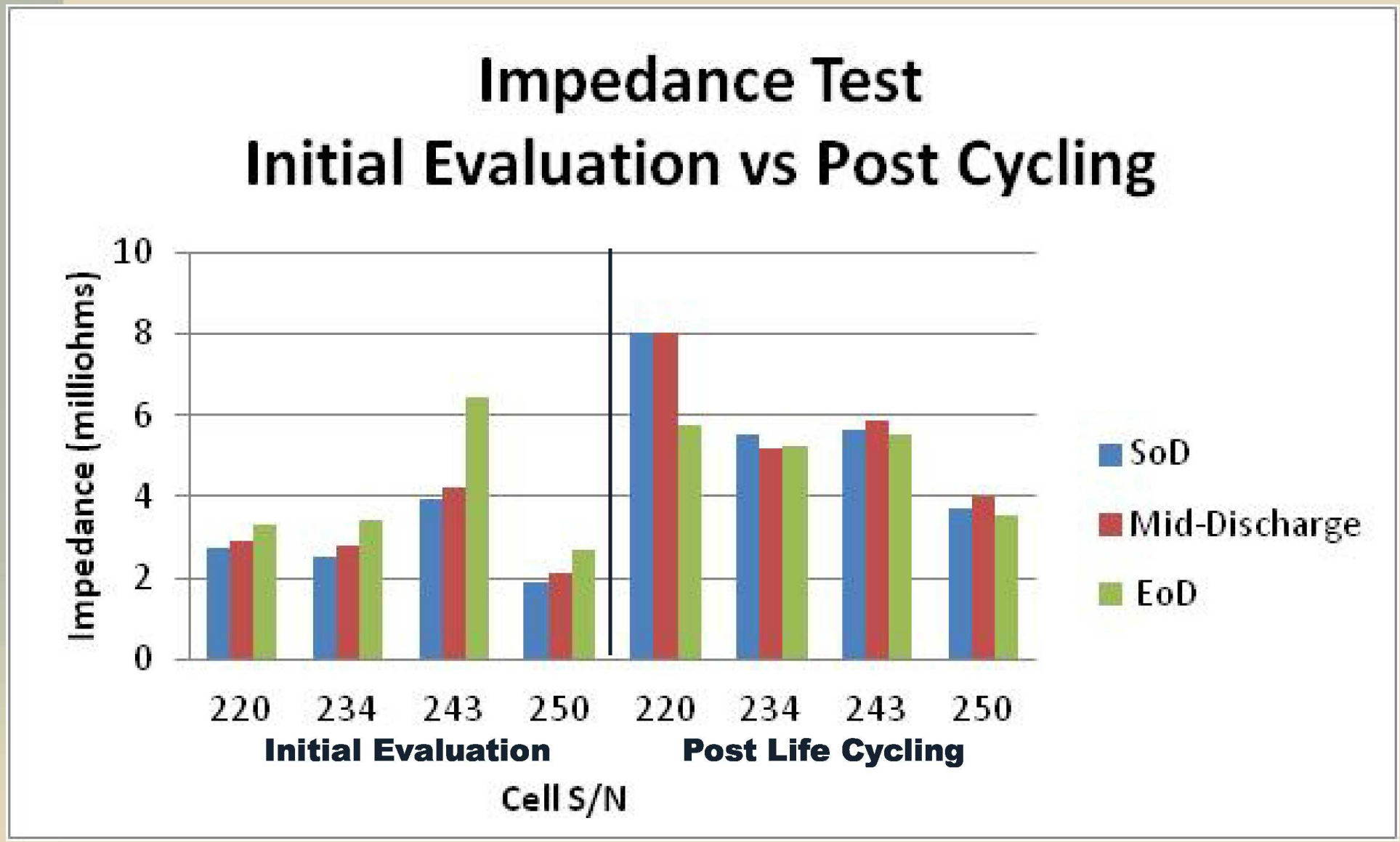
LITHION 50 Ahr Lithium-Ion Cells Life Cycle Test Summary



LITHION 50 Ahr Lithium-Ion Cells Post Cycle Test Summary



LITHION 50 Ahr Lithium-Ion Cells Post Cycle Test Summary



ABSL 5 AHR LITHIUM-ION BATTERY SDO-GEO LIFE CYCLE TEST LRO-LLO LIFE CYCLE TEST

ABSL 5 Ahr Lithium-Ion Battery

Test Pack: AEA Battery Systems Limited (ABSL) 5 Ah Lithium Ion Battery consisting of 32 SONY 18650 cells in 4P/8S configuration

Rated Capacity = 5 Ahr

Prior to testing, battery de-rated to 4 Ahr

Battery was subjected to following tests:

Initial Evaluation – Capacity test at 20°C

State-Of-Charge Test to develop voltage hysteresis curve

SDO-GEO Life Cycle Test – Pack 42NG01

LRO-LLO Life Cycle Test – Pack ABSL02

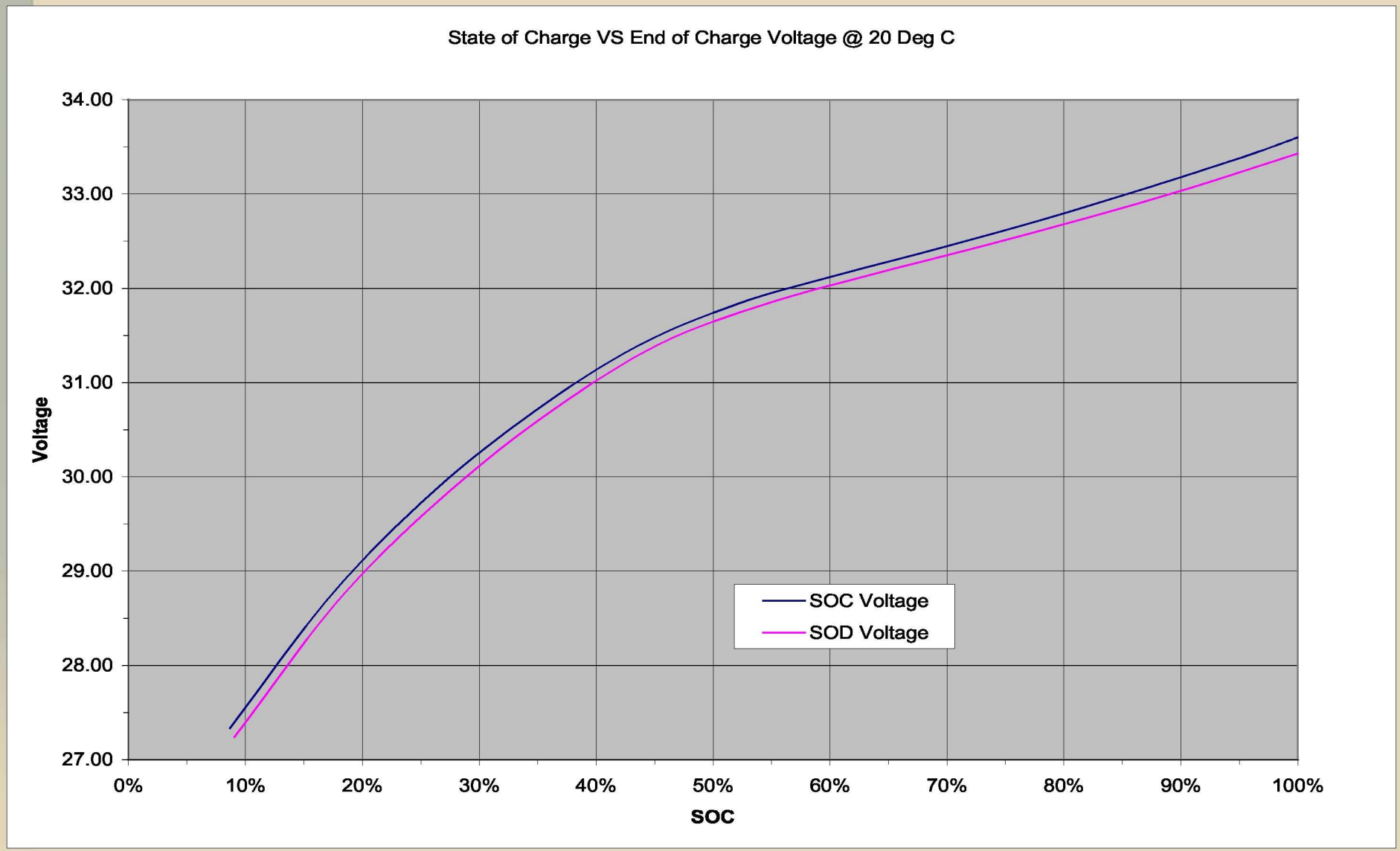
ABSL 5 Ahr Lithium-Ion Battery State Of Charge

SOC Tests performed at 20°C.

Charge Curve.
Charge at C/10 for 1.0 hour. OC for 5 minutes.
Discharge at C/2 to 24.0V.
Increase charge increment by one hour and continue cycling to 33.6V.

Discharge Curve.
Charge at C/10 to 33.6V. OC for 5 minutes.
Discharge at C/2 to 24.0V.
Decrease charge increment by one hour and continue cycling until
minimum of one hour charge is completed.

ABSL 5 Ahr Lithium-Ion Battery State Of Charge Test



ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test

Shadow Regime:

- Eclipse Season = 23 Days
- Test Cycle Duration = 24 hours
- Temperature = 10°C
- Discharge Rate = 0.6C
- Discharge Time = Based on SDO-GEO Discharge Time Graph
- Charge Rate = C/20 to 90% SOC based on SOC Curve.
  - Clamp and taper for remainder of Charge Time.
- Charge Time = 24 hours minus Discharge Time

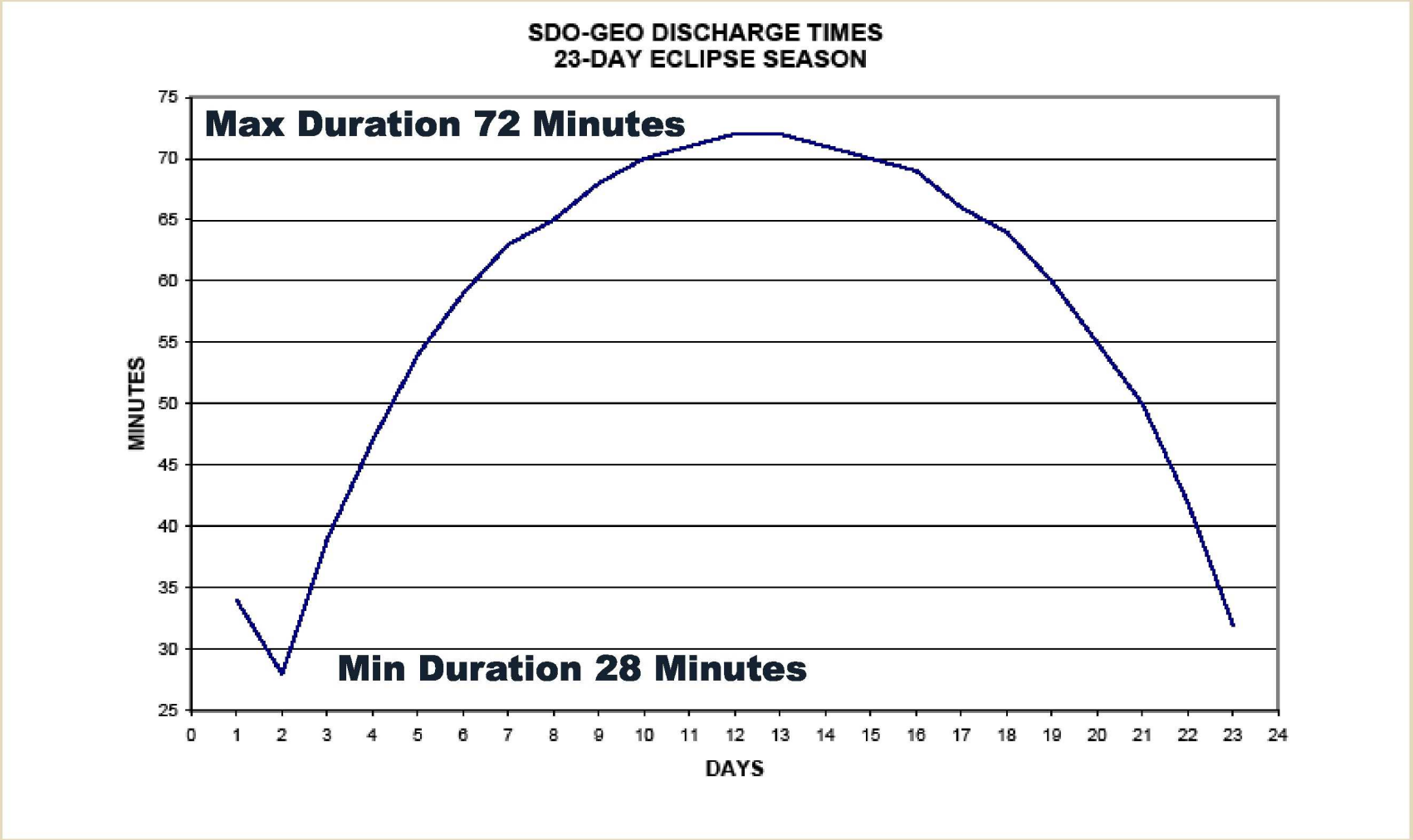
Apply sine wave pulses (~0.2 amps peak-to-peak) as follows:

- 83 Hz pulse during first 30 days of testing.
- 3 Hz pulse thereafter, increasing to 83 Hz for 1 day at start of every month.
- Subsequent frequency changes to be provided by sponsor.

Solstice Regime:

- Solstice Season = 150 days.
- Temperature = 10°C
- Charge at C/20 to 50% SOC, clamp and taper for 149 days.
- For Day 150, charge at C/20 to 90% SOC and taper for 1 day.

ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test



ABSL 5 Ahr Lithium-Ion Battery Test History – SDO-GEO Life Test

11 July 2008 Began Initial Evaluation

28 August 2008 – Began SOC Test

11 December 2008 - Began SDO-GEO Life Cycling

11 December 2008 to 5 January 2009 – 1st Eclipse Season

6 January to 4 June 2009 – 1st Solstice Season

5 June to 3 July 2009 – 2nd Eclipse Season

4 July to 4 December 2009 – 2nd Solstice Season

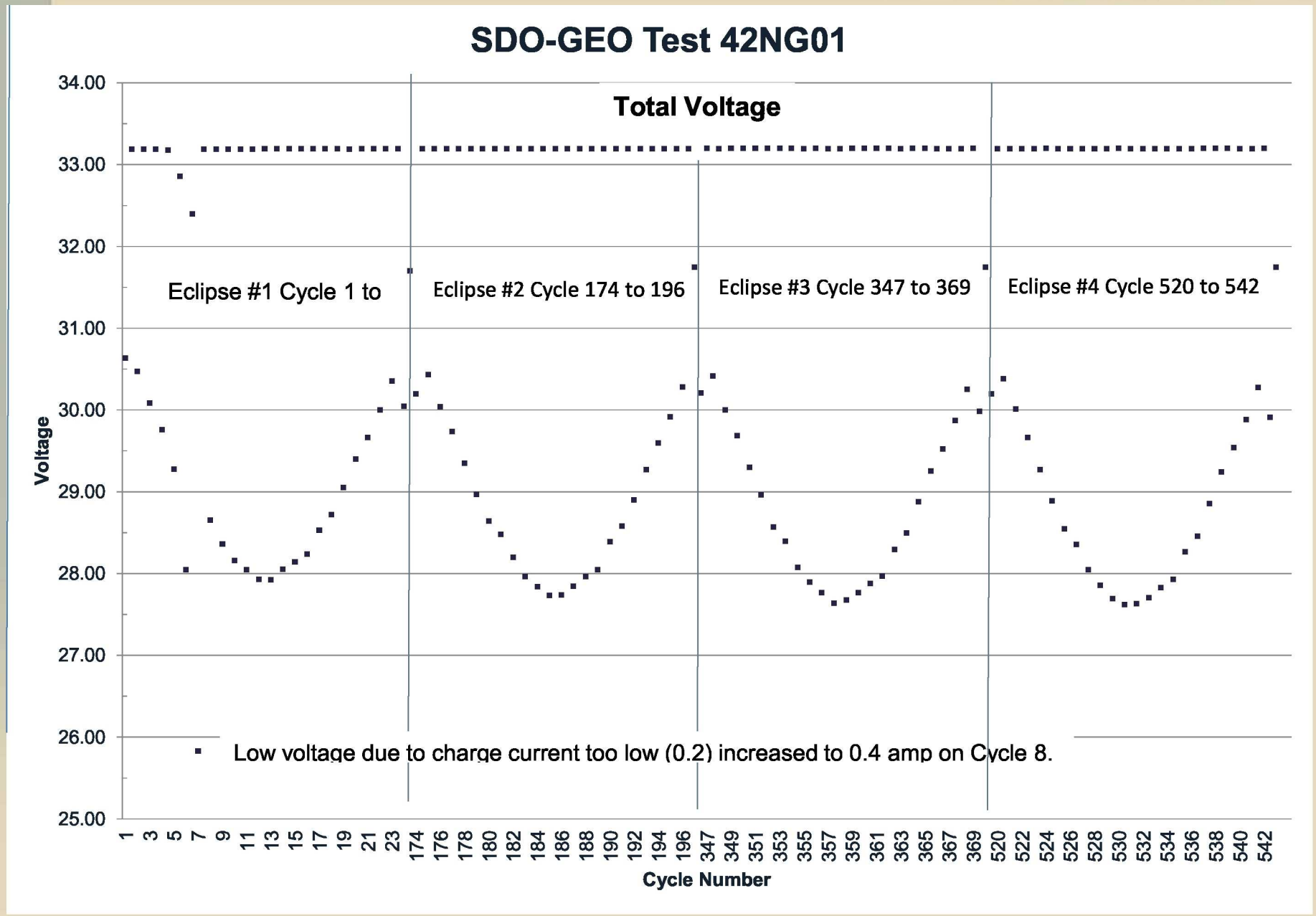
5 to 27 December 2009 - 3rd Eclipse Season

28 December 2009 to 27 May 2010 – 3rd Solstice Season

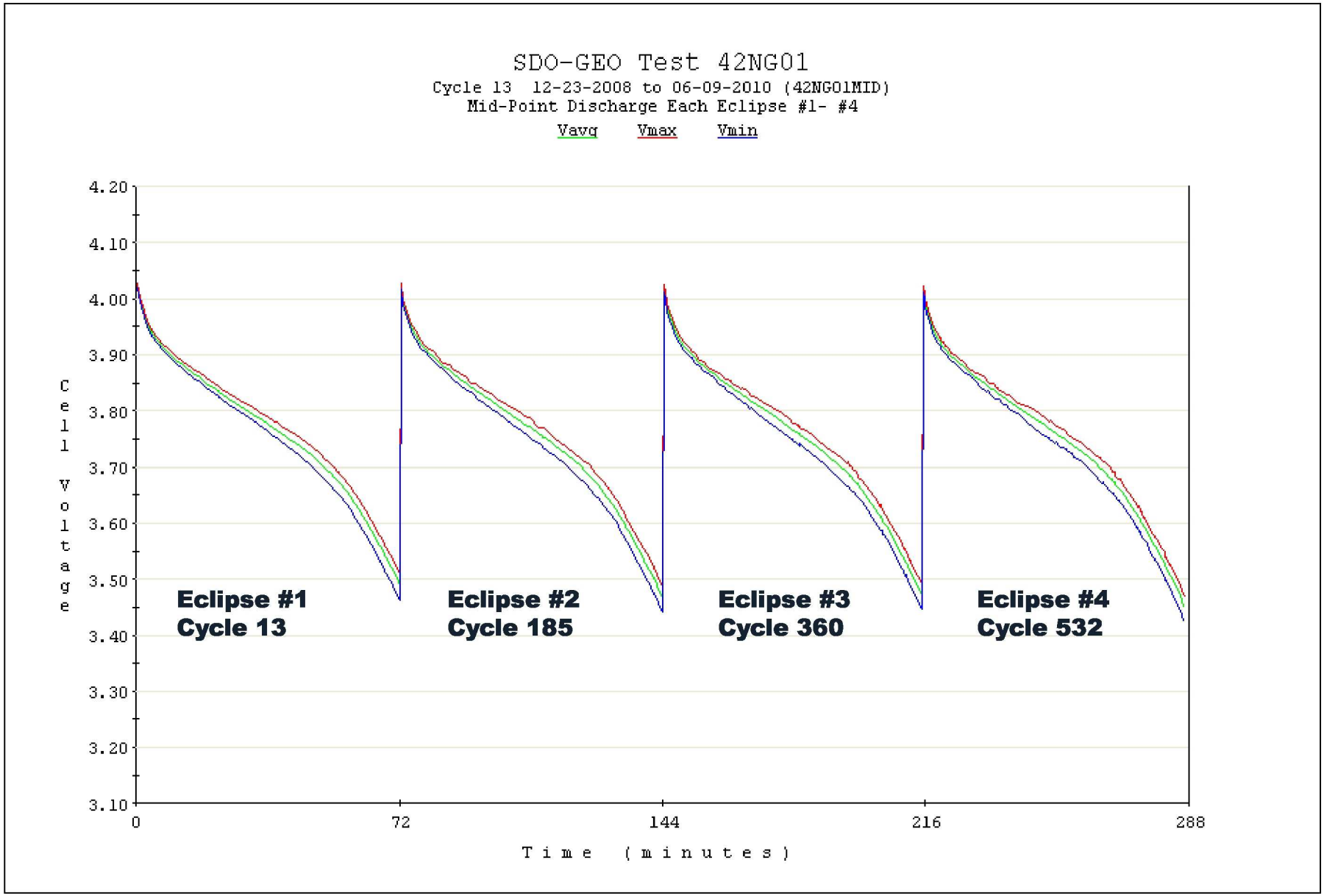
28 May to 22 June 2010 – 4th Eclipse Season

23 June to Present – 4th Solstice Season

ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test



ABSL 5 Ahr Lithium-Ion Battery SDO-GEO Life Cycle Test



ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test

LRO-LLO Life Cycle: 2.5A discharge for 48 minutes (40% DOD) 3A charge to 32V, taper for 65 minute charge time

Every 30 days: 3A Charge to 33.6V, taper for 65 minute charge time 1.5A Discharge for 160 minutes (80% DOD)
Return to Life Cycle profile

ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test

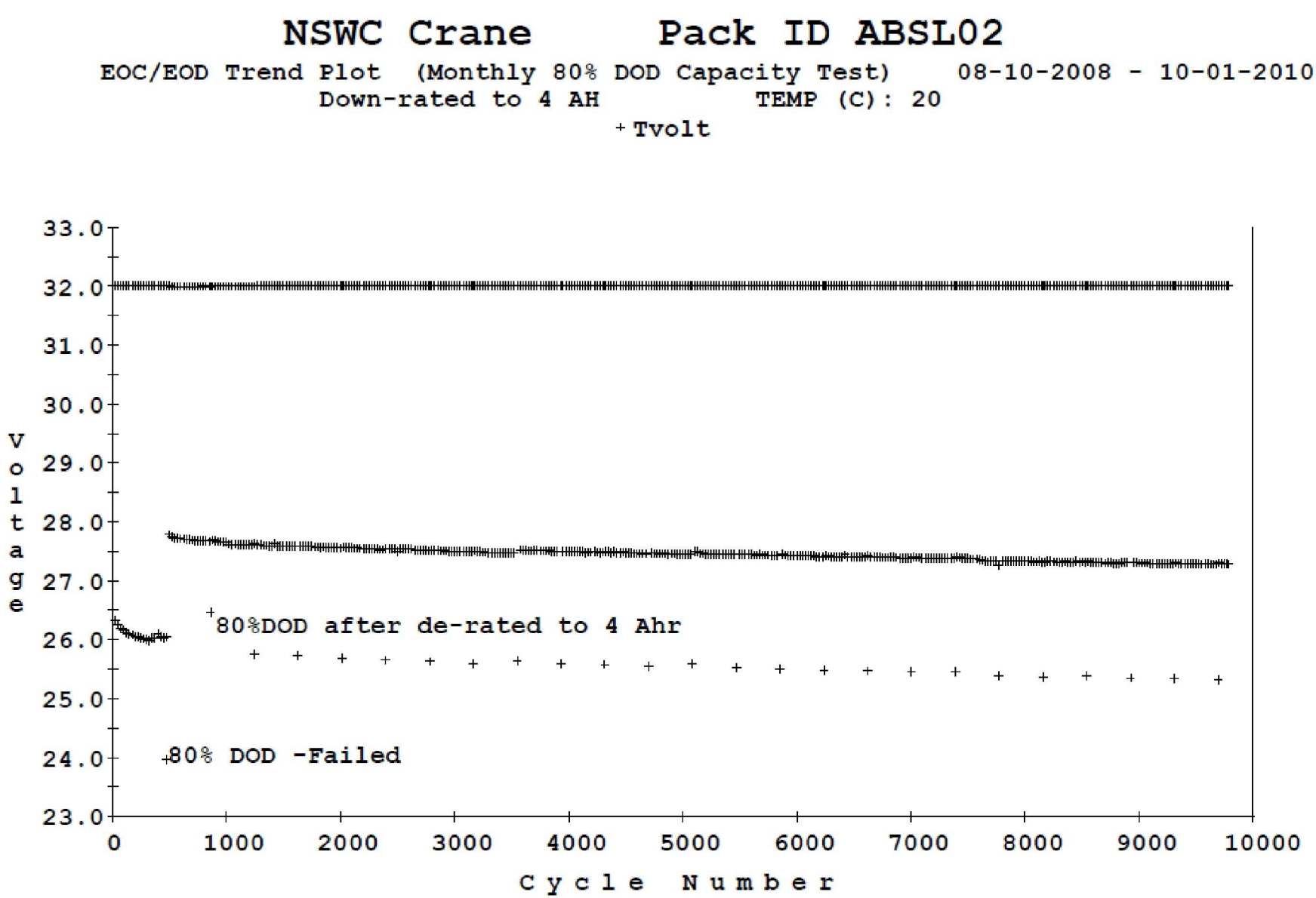
Test History:

7 August 2008 – Began Life Cycling

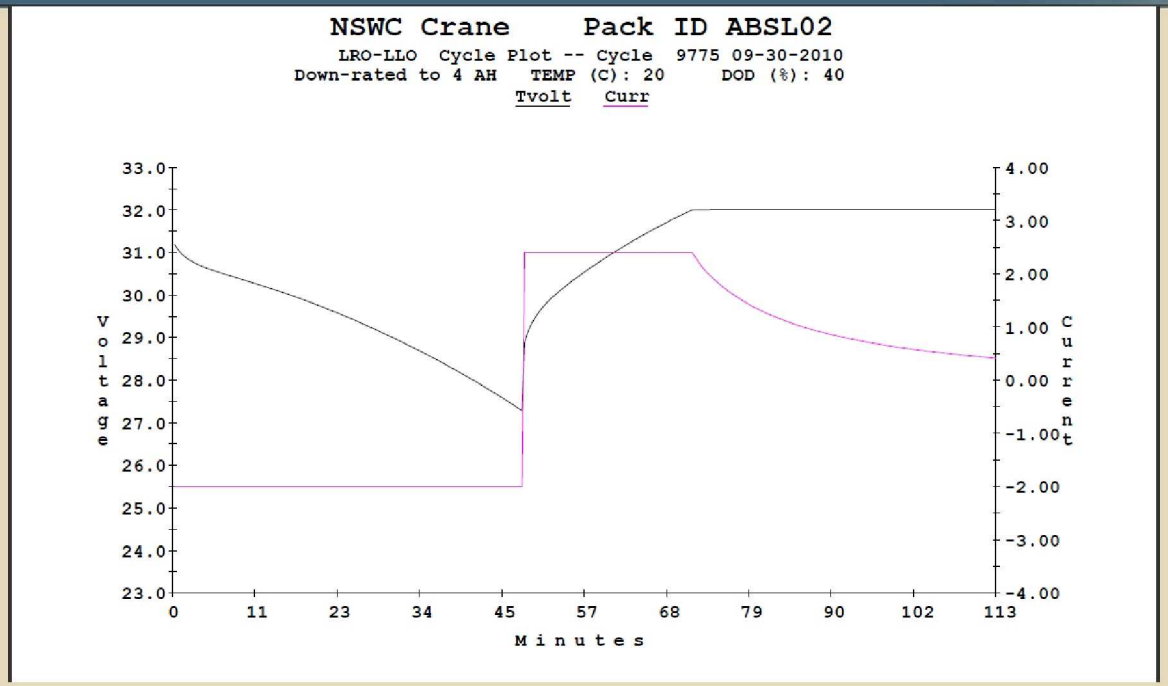
16 September 2008 – Cycle 478. Cells down-rated to 4 Ah due to low cell voltage on 80% DOD deep discharge. Life Cycle profile changed to: 2A discharge for 48 minutes 2.4A charge to 32V, taper for 65 minutes charge time

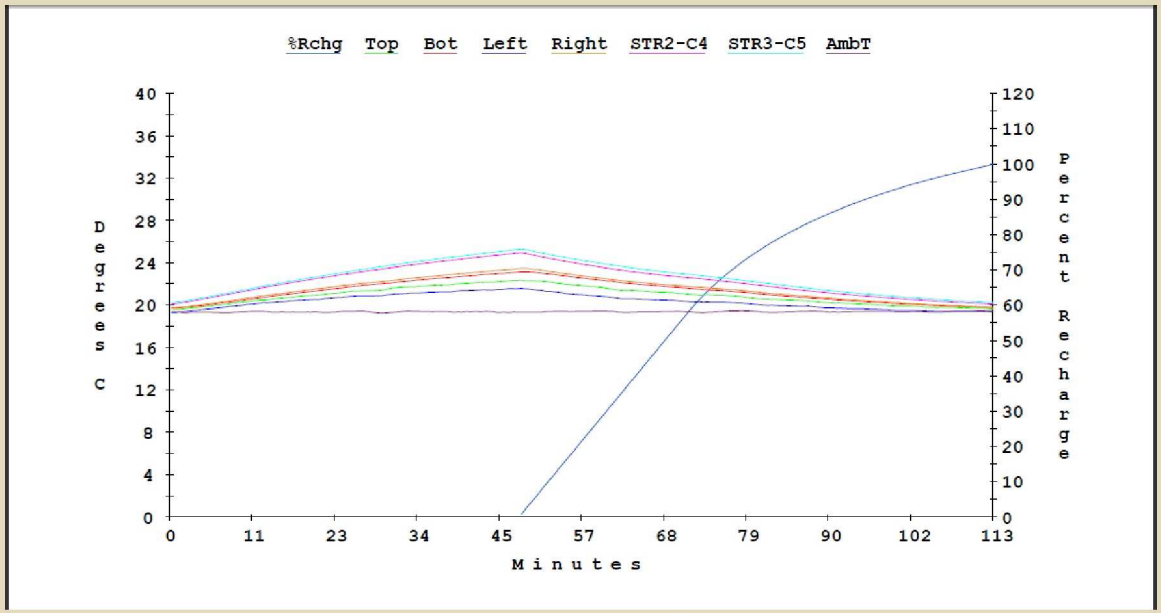
31 October 2010 – Continue testing completed cycle 10,175

ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test



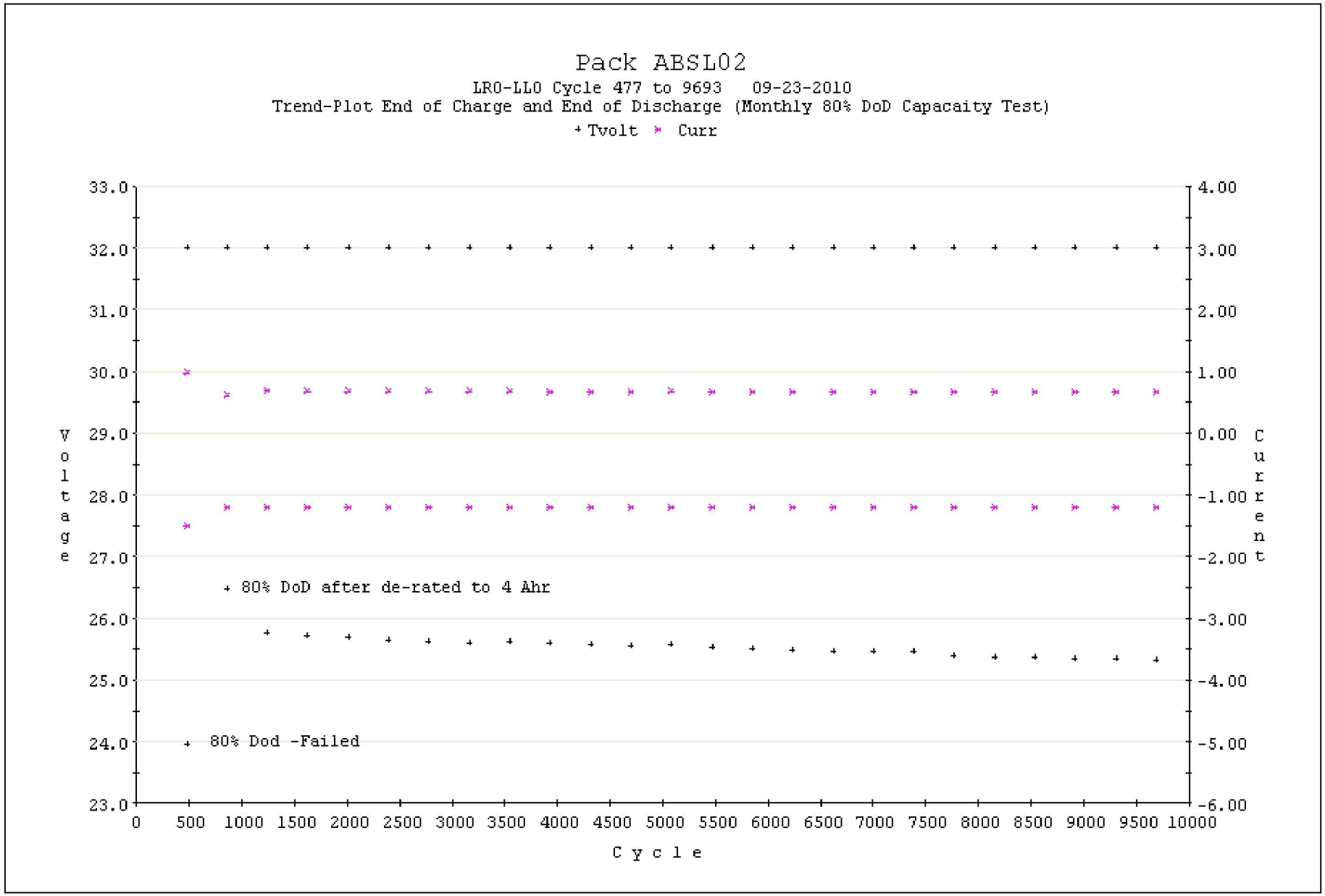
ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test





FINAL – Distribution Approved NASA Goddard Space Flight Center

ABSL 5 Ahr Lithium-Ion Battery LRO-LLO Life Cycle Test



A123 40 AHR LITHIUM-ION BATTERY

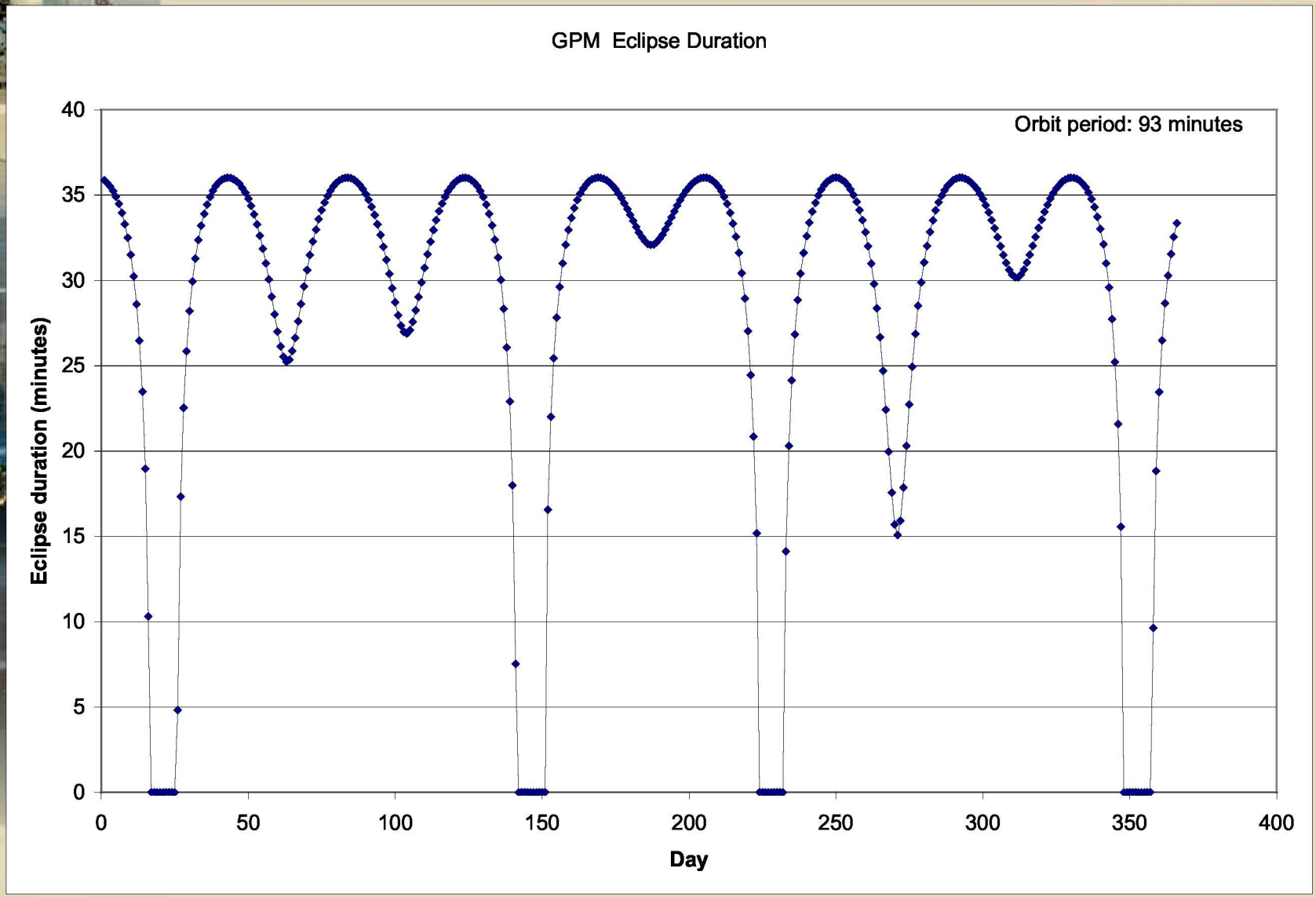
GPM LIFE CYCLE TEST
MMS LIFE CYCLE TEST

A123 40 Ahr Lithium-Ion Battery GPM & MMS Life Cycle Test

Test parameters

- Two batteries consisting of 160 cells each.
  - 8 series strings of 20 cells in parallel.
  - Cell Type: ANR26650-M1, Capacity 2.3Ahr, Voltage 3.3V
- Manufactured by A123 Systems
- Capacity Rated 44 Ahr, De-rated to 40 Ahr
- Battery Voltage – 28.8 volts
- GPM test profile – Pack ID 66NL40
  - Temperature = 20ºC
  - Discharge at C/2 (20A) for specified time
  - Charge at C/2 (20A) charge with a voltage clamp of 28.8V for a remainder of 93 minute orbit.
  - 15 orbits per day

A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



Temperature = 20°C

Discharge at C/2 (20A) for specified time

Charge at C/2 (20A) charge with a voltage clamp of 28.8V for a remainder of 93 minute orbit.

15 orbits per day

A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test

Test History – GPM Life Cycle Test Pack 66NL40

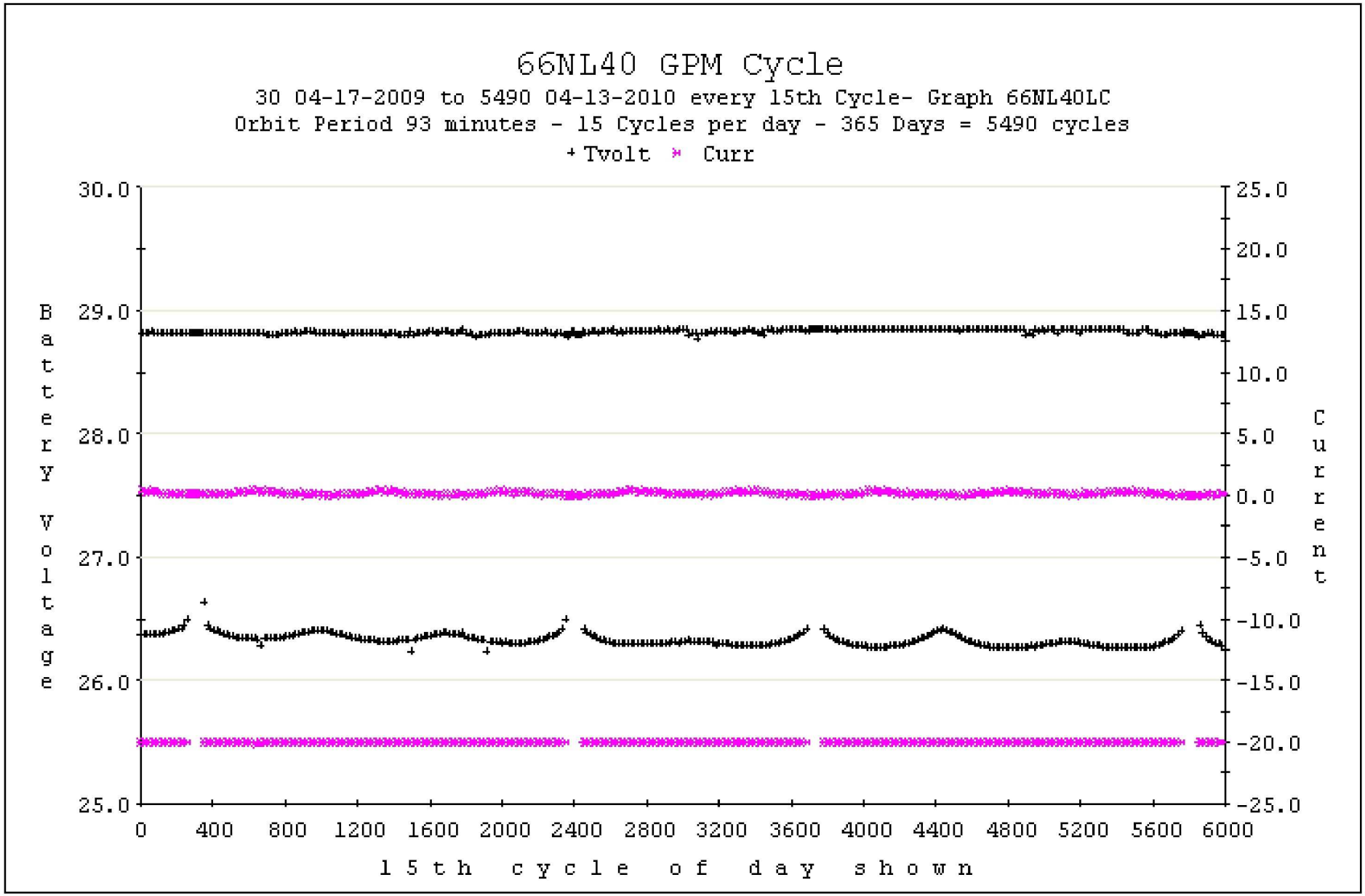
Characterization tests:

- **Capacity Test 20ºC – 41.8 Ahr**
- **Capacity Retention Test 20ºC – 40.5 Ahr**
- **Capacity Test 0ºC – 41.1 Ahr**
- **Capacity Test 40ºC – 41.8 Ahr**
- **Capacity Test 20ºC – 41.8 Ahr**

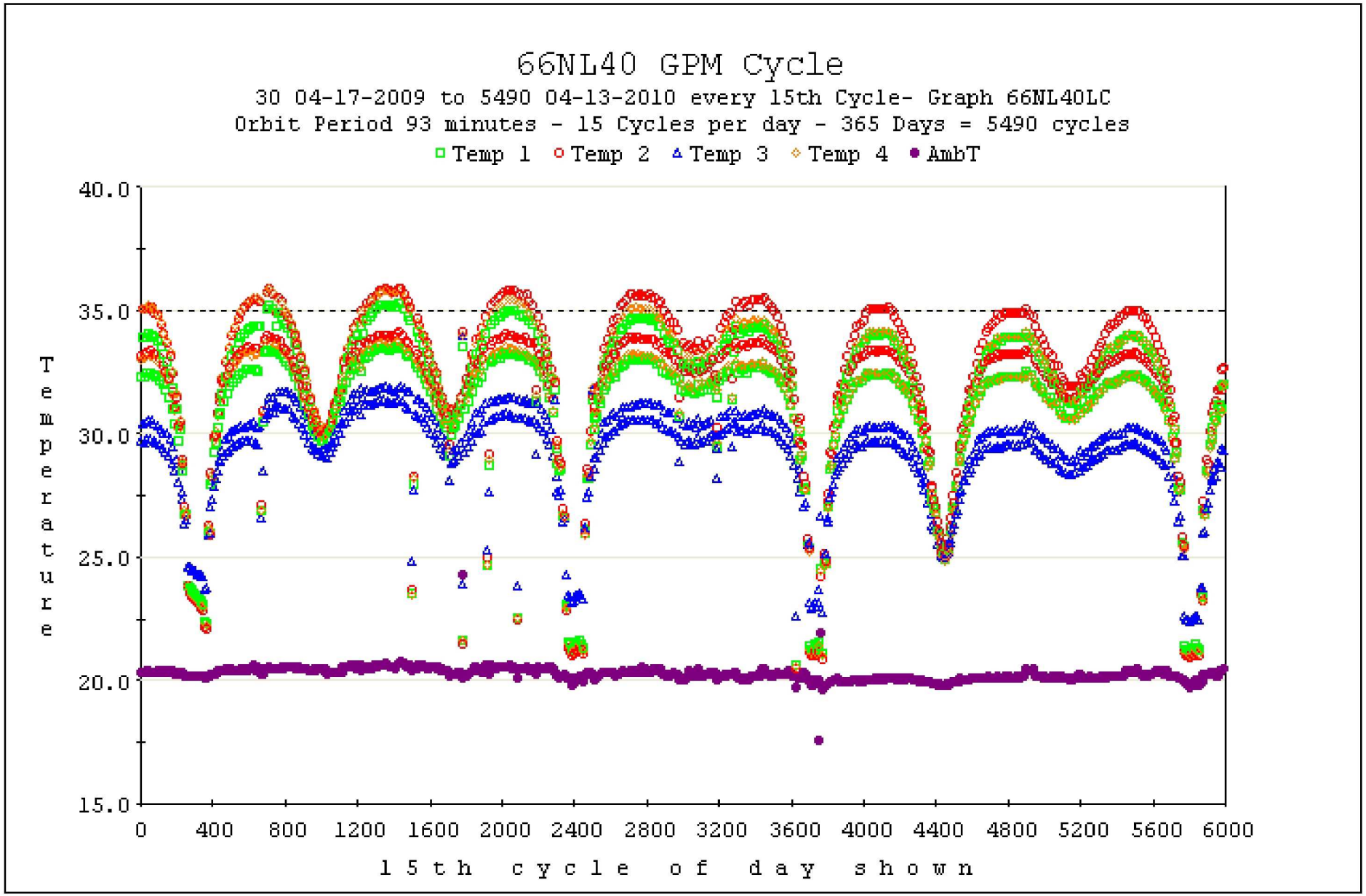
Began Life Cycle Test – April 2009

Test Discontinued – 19 April 2010 Completed 365 days of GPM profile -5494 Cycles

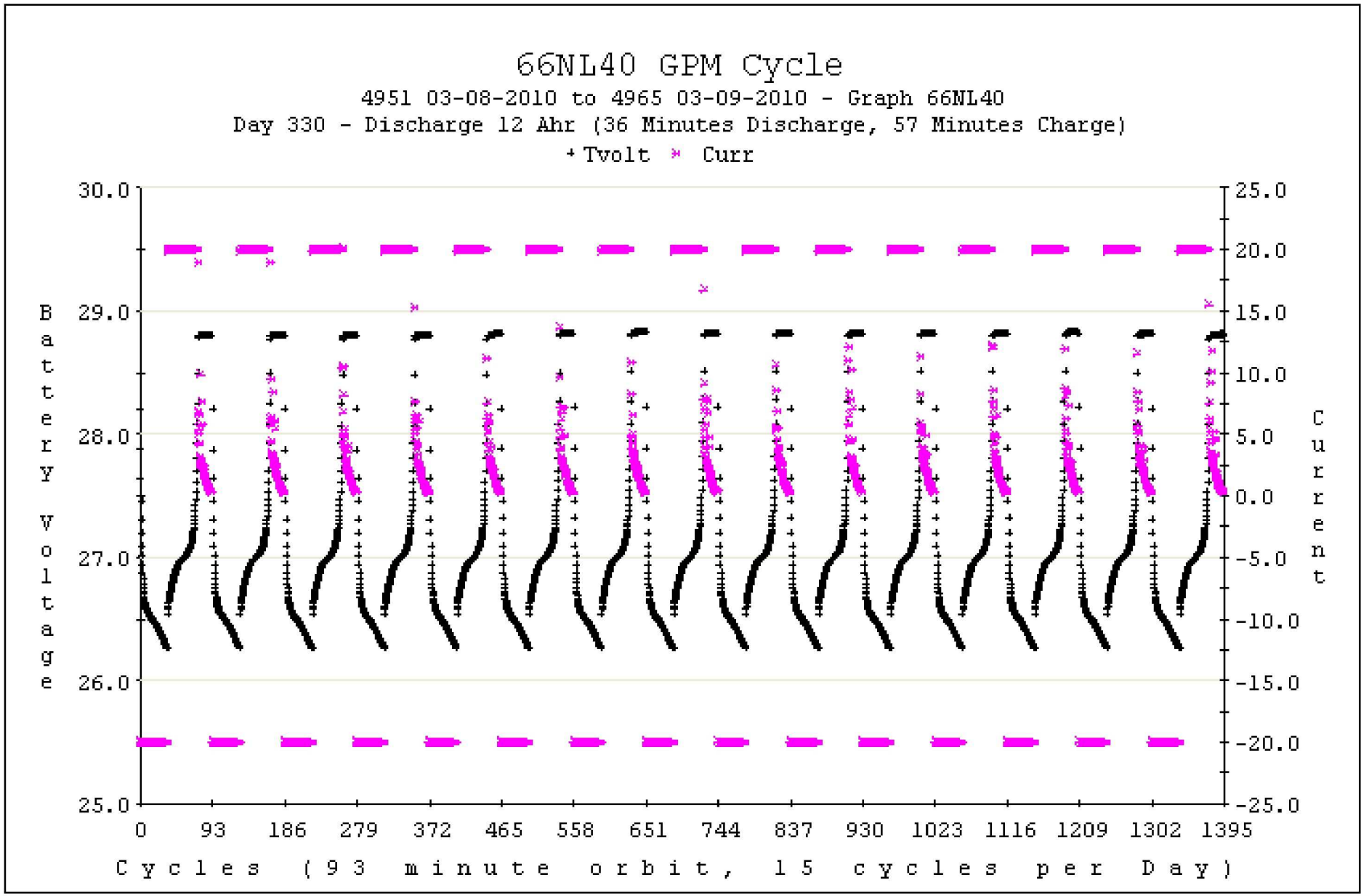
A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



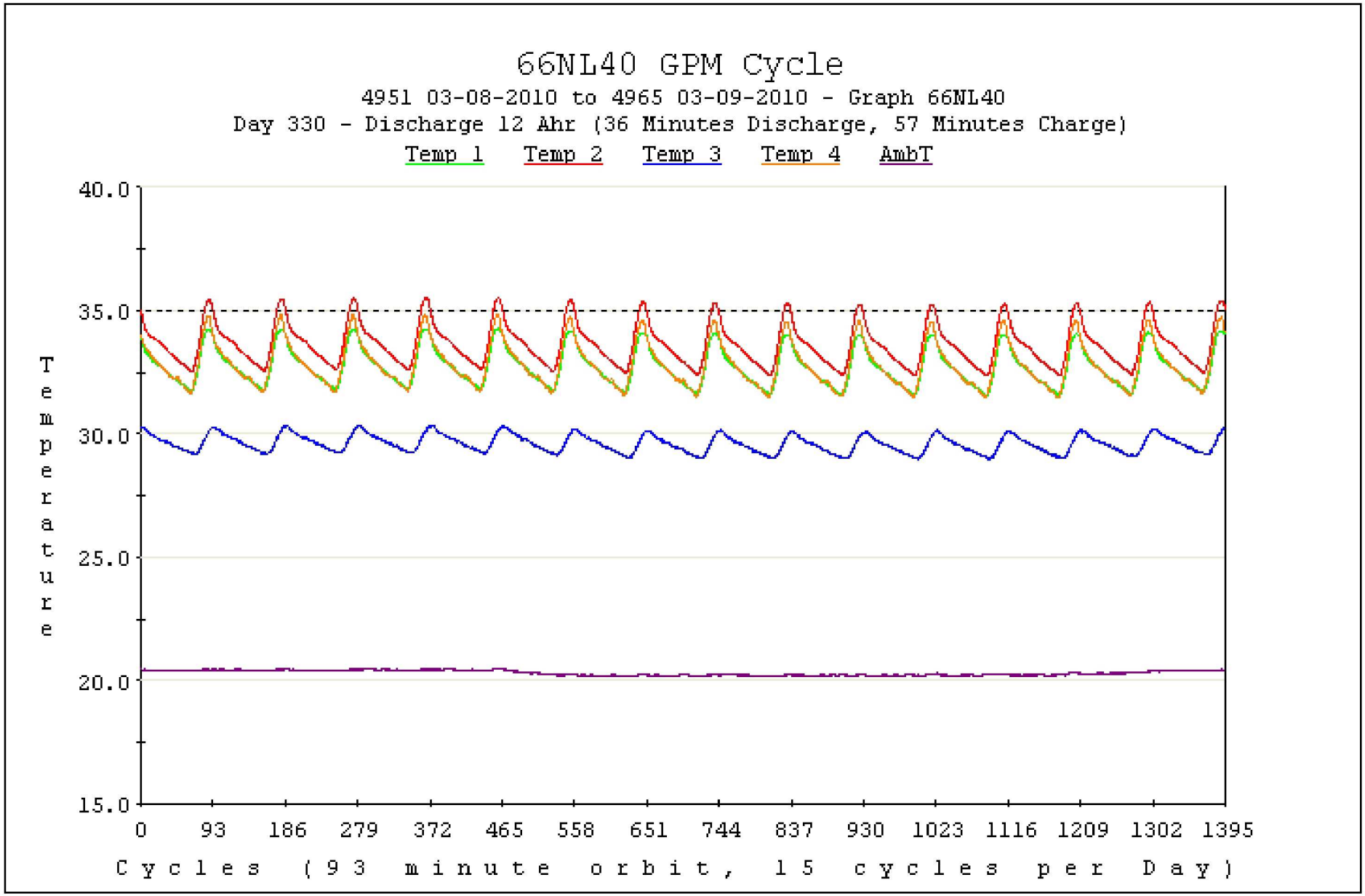
A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



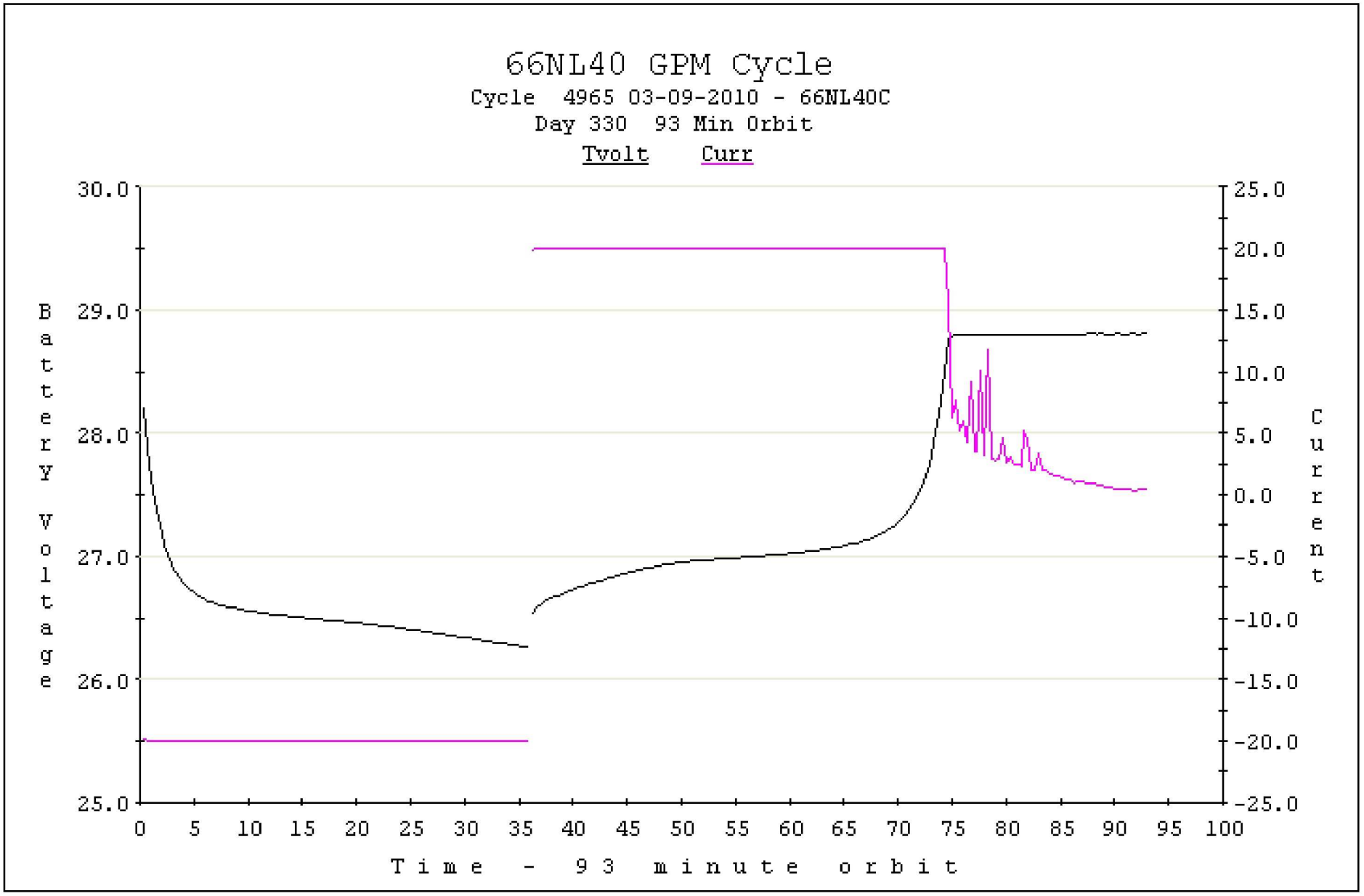
A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



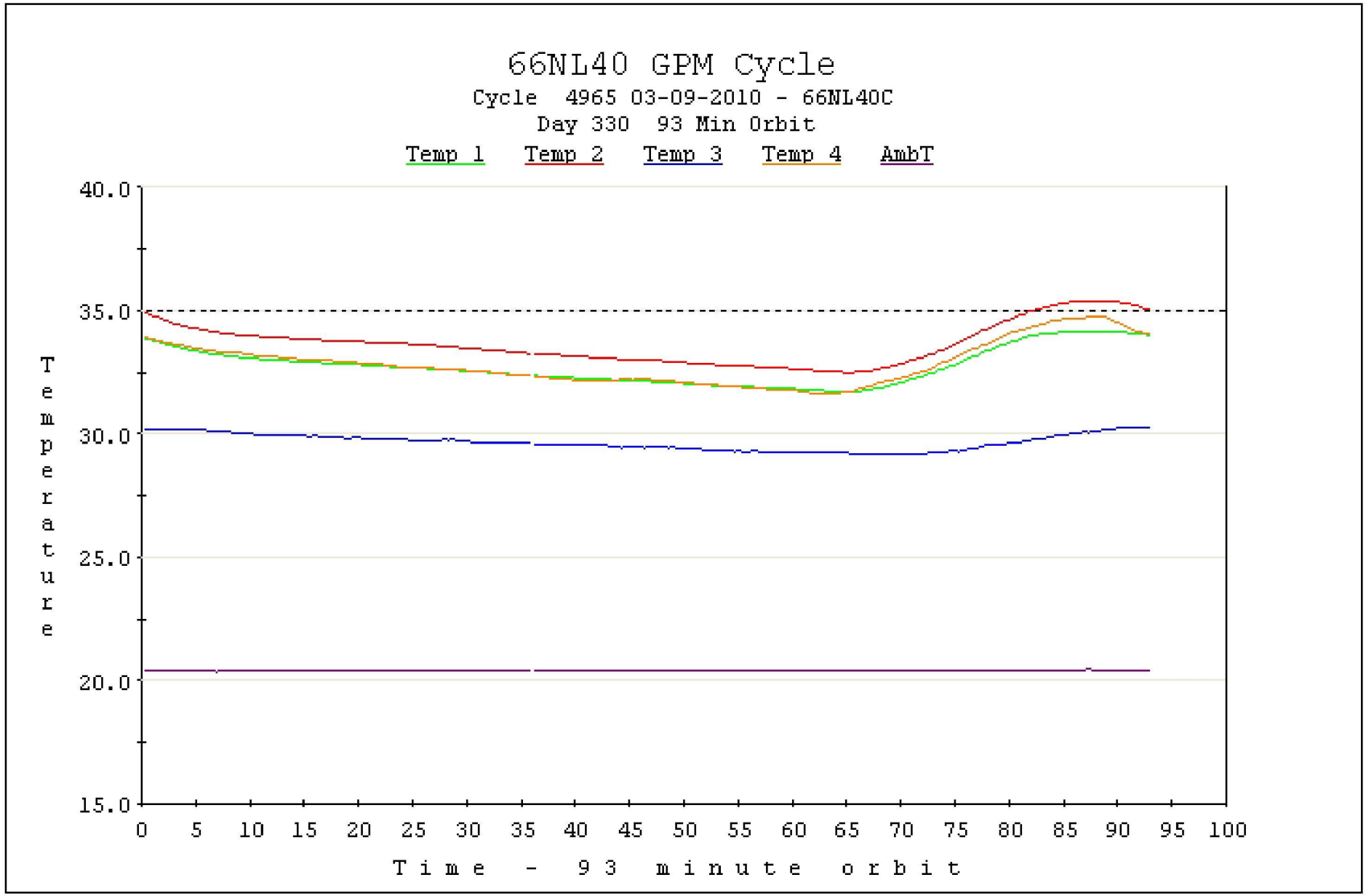
A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



A123 40 Ahr Lithium-Ion Battery GPM Life Cycle Test



A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test

MMS test profile: Pack ID 67NL41

Phase 1 – At 20ºC, Discharge 50% DoD in 4 hrs (approx 5A), Charge for 20 hrs at 3.3A to 28.8v voltage clamp for 6 months.

Phase 2 – At 20ºC, Discharge50% DoD in 2 hrs (approx 10A), Charge for 22 hrs at 3.3A to 28.8v voltage clamp for 6 months.

Annually perform residual capacity and 20ºC capacity and charge retention test.

A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test

Test History:

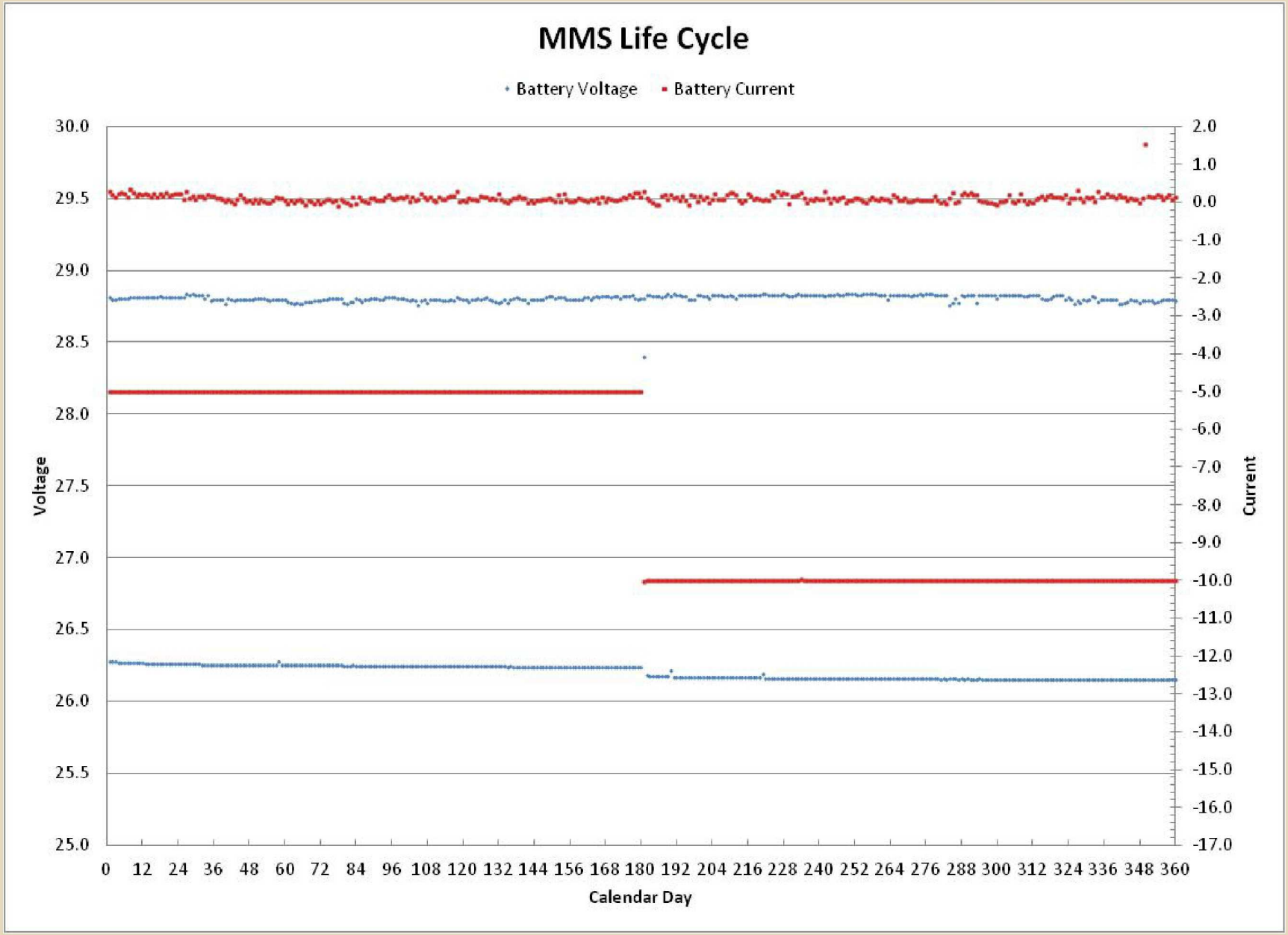
- **Characterization tests:**
  - **Capacity Test 20ºC – 39.5 Ahr**
  - **Capacity Retention Test 20ºC – 38.3 Ahr**
  - **Capacity Test 0ºC – 38.5 Ahr**
  - **Capacity Test 40ºC – 39.6 Ahr**
  - **Capacity Test 20ºC – 39.6 Ahr**
- **Began Life Cycle Test – 23 April 2009**

Test Status

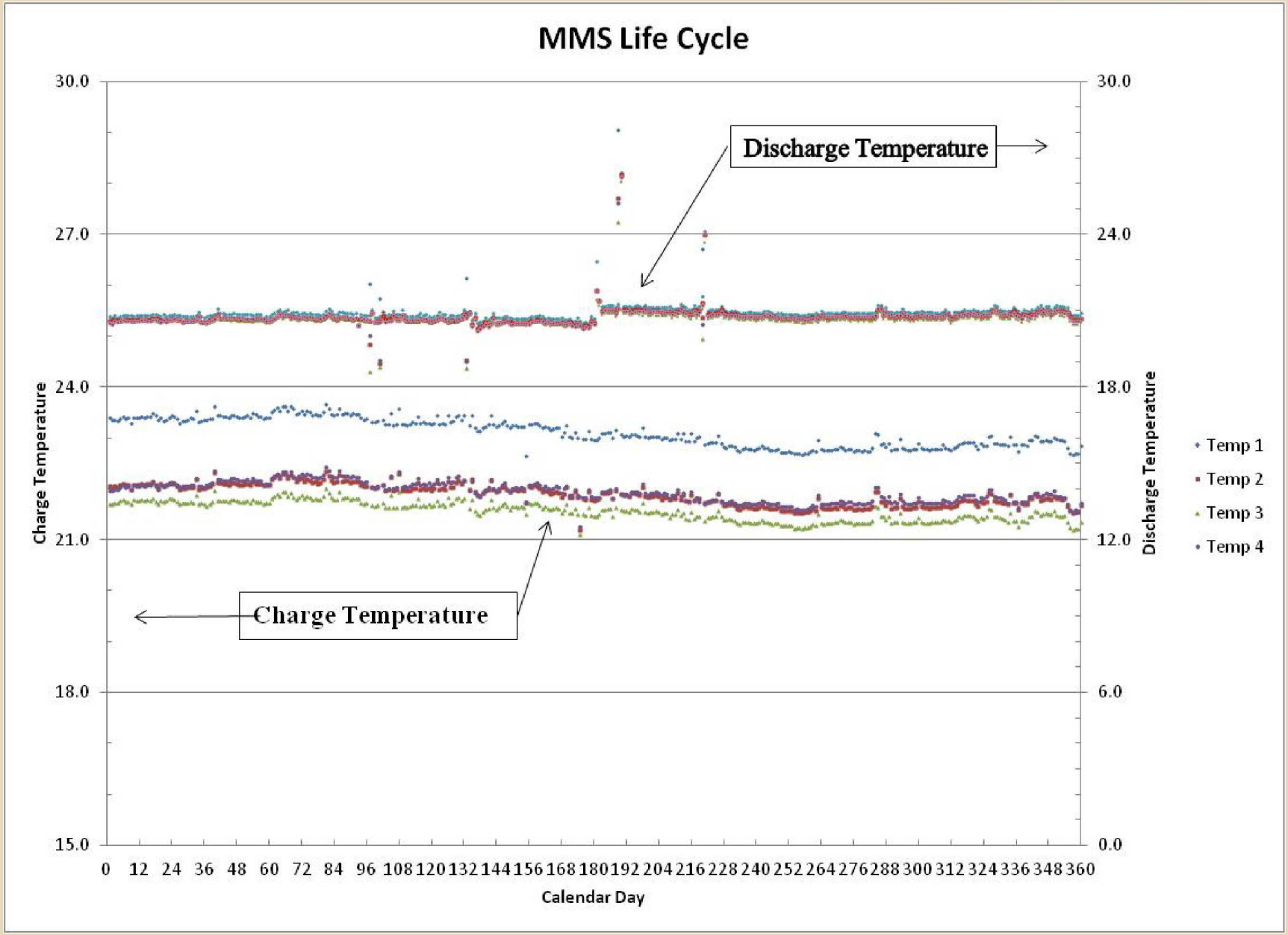
23 October 2009 - Completed 180 cycles at 50% DoD at 5 amp rate
23 April 2010 – Completed 180 cycles at 50% DoD at 10 amp rate
Test Discontinued 23 May 2010

Performed Annual Performance Tests – Complete 11 June 2010

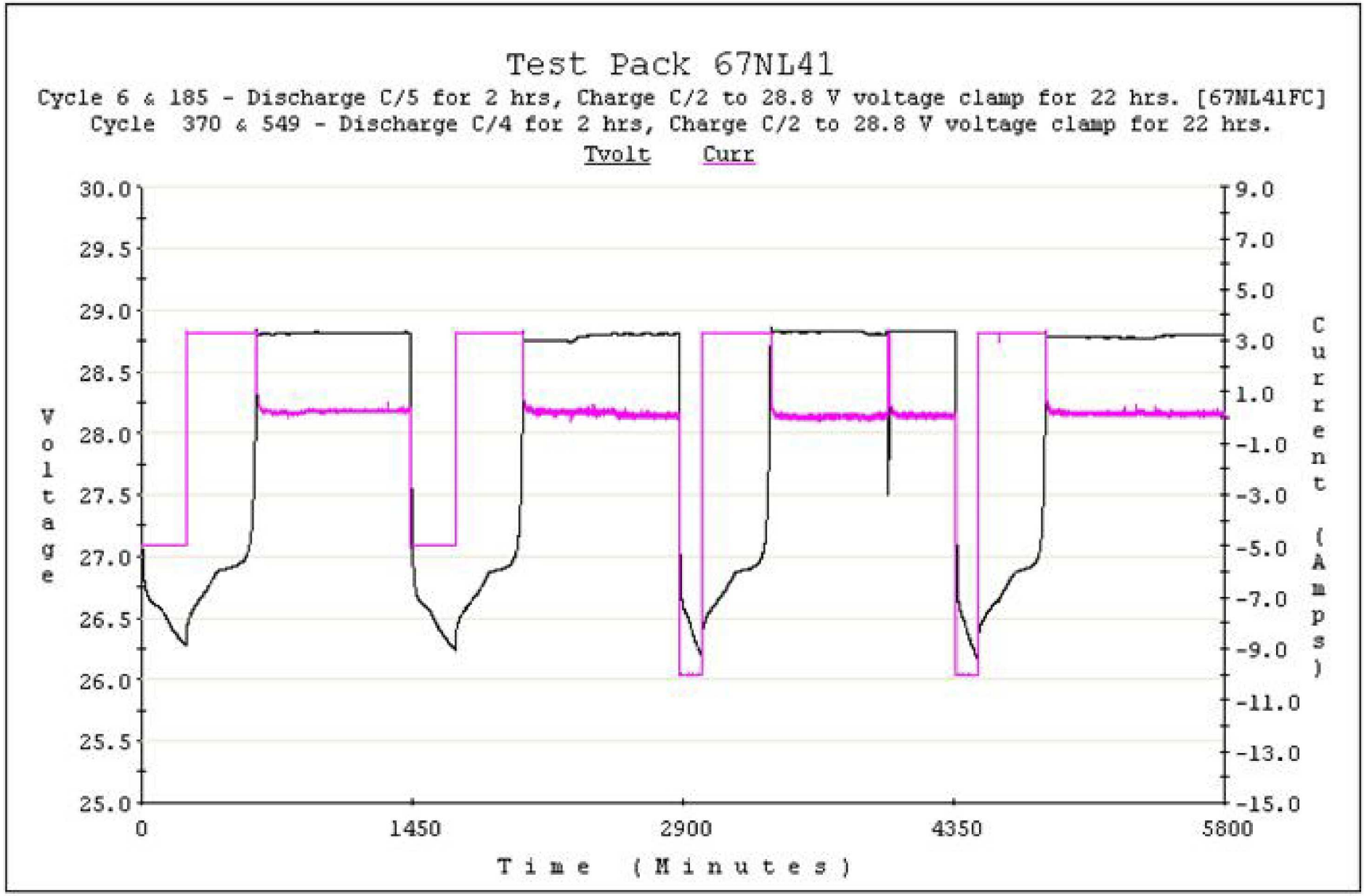
A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test



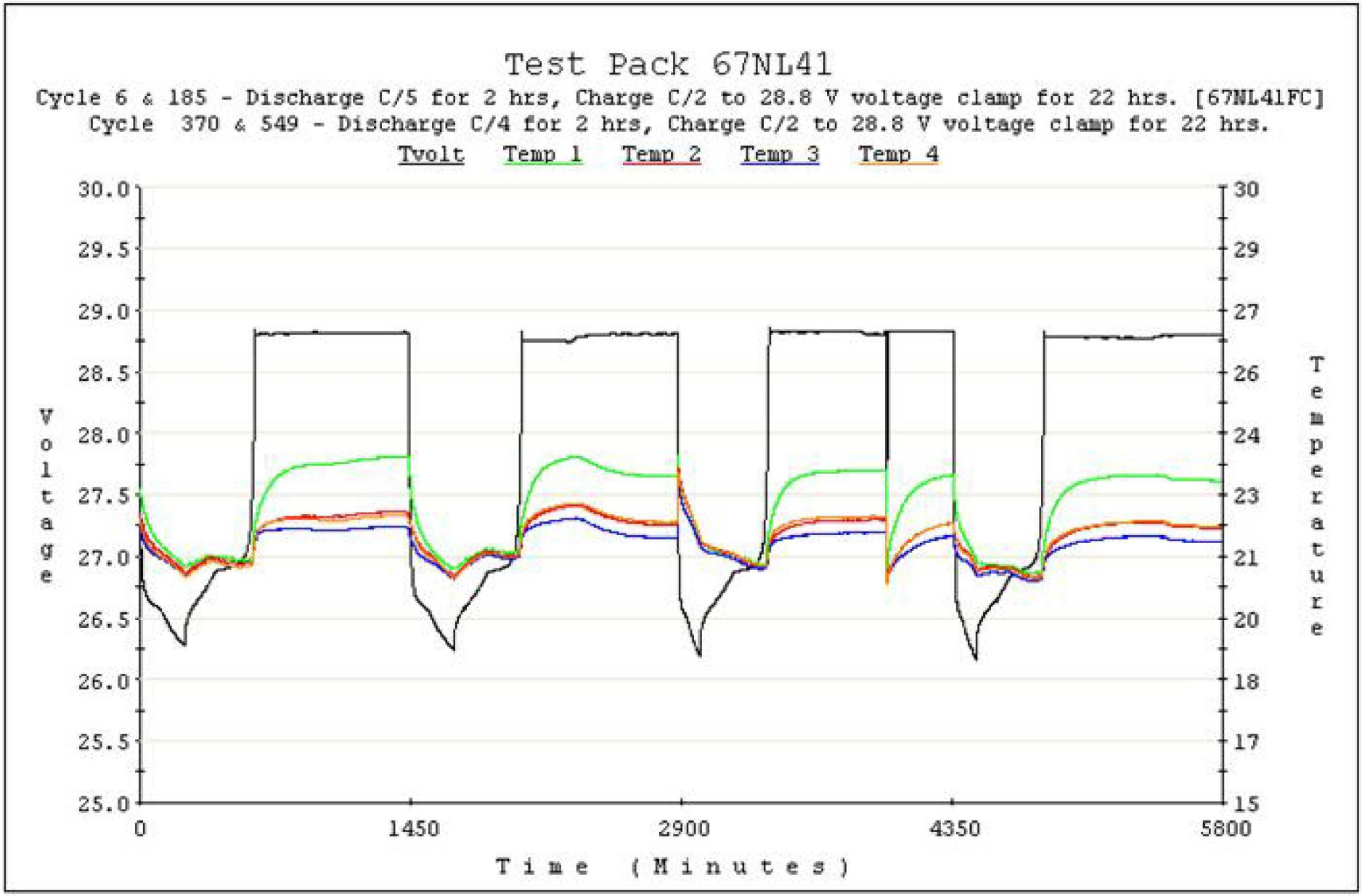
A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test



A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test



A123 40 Ahr Lithium-Ion Battery MMS Life Cycle Test



A123 40 Ahr Lithium-Ion Battery GPM & MMS Life Cycle Test

Performance Test Results:

After 1 yr Test	GPM	Loss
Capacity Test 20°C –	37.5	4.3 Ahr
Charge Retention 20°C –	36.6	3.9 Ahr
Capacity Test 20°C –	37.9	4.0 Ahr
	MMS	
Capacity Test 20°C –	38.2	1.3 Ahr
Charge Retention 20°C –	37.3	1.0 Ahr
Capacity Test 20°C –	38.2	1.4 Ahr

A123 40 Ahr Lithium-Ion Battery GPM & MMS Life Cycle Test

Characterization tests: GPM	Initial	Post Cycling
Capacity Test 20ºC –	41.8	37.5 Ahr
Capacity Retention Test 20ºC –	40.5	36.6 Ahr
Capacity Test 0ºC –	41.1	37.5 Ahr
Capacity Test 40ºC –	41.8	38.3 Ahr
Capacity Test 20ºC –	41.8	38.4 Ahr

Loss of 3-4 Ahr after 1 year

Characterization tests: MMS		
Capacity Test 20ºC –	39.5	38.2 Ahr
Capacity Retention Test 20ºC –	38.3	37.3 Ahr
Capacity Test 0ºC –	38.5	38.0 Ahr
Capacity Test 40ºC –	39.6	38.7 Ahr
Capacity Test 20ºC –	39.6	39.0 Ahr

Loss of .4 to 1 Ahr after 1 year